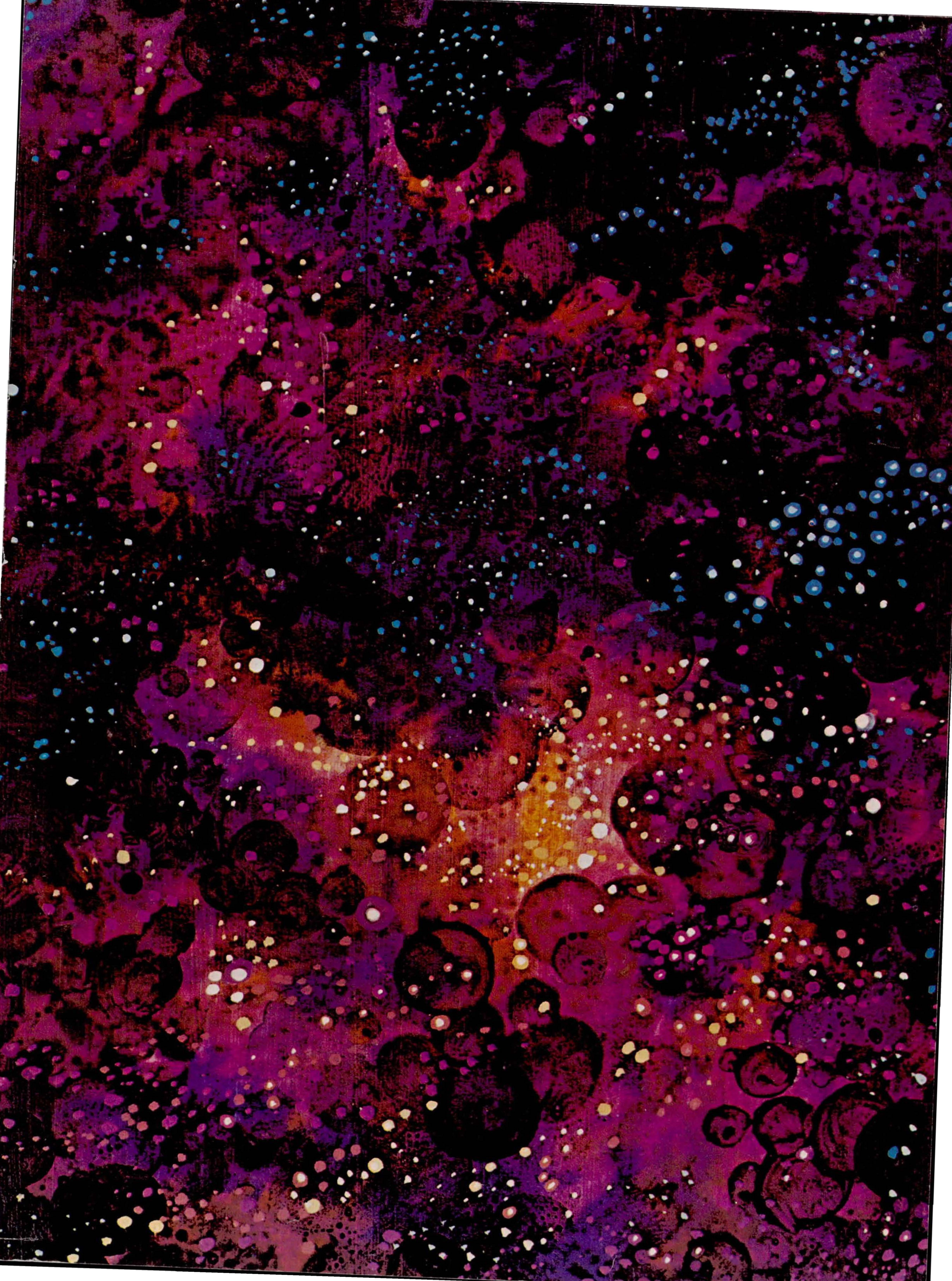
Space Settlements

A Design Study

National
Aeronautics and
Space
Administration



NASA SP-413

Space Settlements

A Design Study

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THE 1975 SUMMER FACULTY FELLOWSHIP PROGRAM IN ENGINEERING SYSTEMS DESIGN

under the sponsorship of:

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and

AMERICAN SOCIETY FOR ENGINEERING EDUCATION

and directed by:

AMES RESEARCH CENTER

and

STANFORD UNIVERSITY

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Foreword

SPACE SETTLEMENTS: A DESIGN STUDY

The question, "What is feasible?" can be finally answered only by future historians. If in the 14th and 15th Centuries when new technology first made transoceanic voyages possible, European rulers had inquired what they should do with this new capability, no man could have been long-headed enough to perceive all the possibilities, nor persuasive enough to communicate his vision to others. We now realize that technology is but a part of any broad stride taken by man. A perception of advantage to be gained, resolve, organization, and a continuity of effort – some of the elements that must combine with technology to effect a major human advance – is indeed vital.

Space exploration, an active pursuit for less than two decades, has already displayed an extraordinary power to alter our viewpoints and stretch our minds. The concept of spacecraft Earth, a sphere of finite resources and ominous pollution, became pervasive and powerful at the same time we first received good photographs of our planetary home. The study summarized in this volume is another mind-stretcher. As explained on the following page, settlement in space is not an authorized program, and no man can now say if or when such a dazzling venture may be formally undertaken. But by their efforts to put numbers on an idea, to assess the human and economic implications as well as technical feasibility, the participants in this effort have provided us with a vision that will engage our imagination and stretch our minds.

James C. Fletcher
Administrator
National Aeronautics
and Space Administration
October 1, 1976

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Preface

The following report grew out of a 10-week program in engineering systems design held at Stanford University and the Ames Research Center of the National Aeronautics and Space Administration during the summer of 1975. This program, sponsored jointly by NASA and the American Society for Engineering Education, brought together nineteen professors of engineering, physical science, social science, and architecture, three volunteers, six students, a technical director, and two co-directors. This group worked for ten weeks to construct a convincing picture of how people might permanently sustain life in space on a large scale.

This report, like the design itself, is intended to be as technologically complete and sound as it could be made in ten weeks, but it is also meant for a readership beyond that of the aerospace community. Because the idea of colonizing space has awakened strong public interest, the report is written to be understood by the educated public and specialists in other fields. It also includes considerable background material. A table of units and conversion factors is included to aid the reader in interpreting the units of the metric system used in the report.

The goal of the summer study was to design a system for the colonization of space. The study group was largely self-organized; it specified important subsidiary goals, set up work groups, and elected its project managers and committee heads. There were three project managers; each served for three weeks during which he assigned tasks, coordinated activities and developed the outline of the final report. As a consequence of this organization, the report represents as nearly as is possible the views of the entire study group. The conclusions and recommendations are the responsibility of the participants and should not be ascribed to any of the sponsoring organizations; NASA, ASEE, or Stanford University.

An effort of the magnitude of this design study could not have been possible without major contributions by many individuals. The co-directors, Richard Johnson of NASA and William Verplank of Stanford, made available to and guided participants in the use of the resources of the Ames Research Center and Stanford University. Their continuing helpfulness and timely assistance were important contributions to the successful conclusion of the project.

The technical director, Gerard K. O'Neill of Princeton University, made essential contributions by providing information based on his notes and calculations from six years of prior work on space colonization and by carefully reviewing the technical aspects of the study.

So many able and interesting visitors contributed to the study participants' understanding of the problem of designing a workable system for colonizing space that it is not feasible to thank them all here. Nevertheless, it is appropriate to acknowledge those from whom the study group drew especially heavily in the final design. In particular Roger Arno, Gene Austin, John Billingham, Philip Chapman, Hubert P. Davis, Jerry Driggers, Peter Glaser, Albert Hibbs, Arthur Kantrowitz, Ken Nishioka, Jesco von Putkammer, and Gordon Woodcock are thanked for their help and ideas.

The assistance of Eric Burgess, who made major contributions to the editorial work, is also gratefully acknowledged.

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Table of Contents

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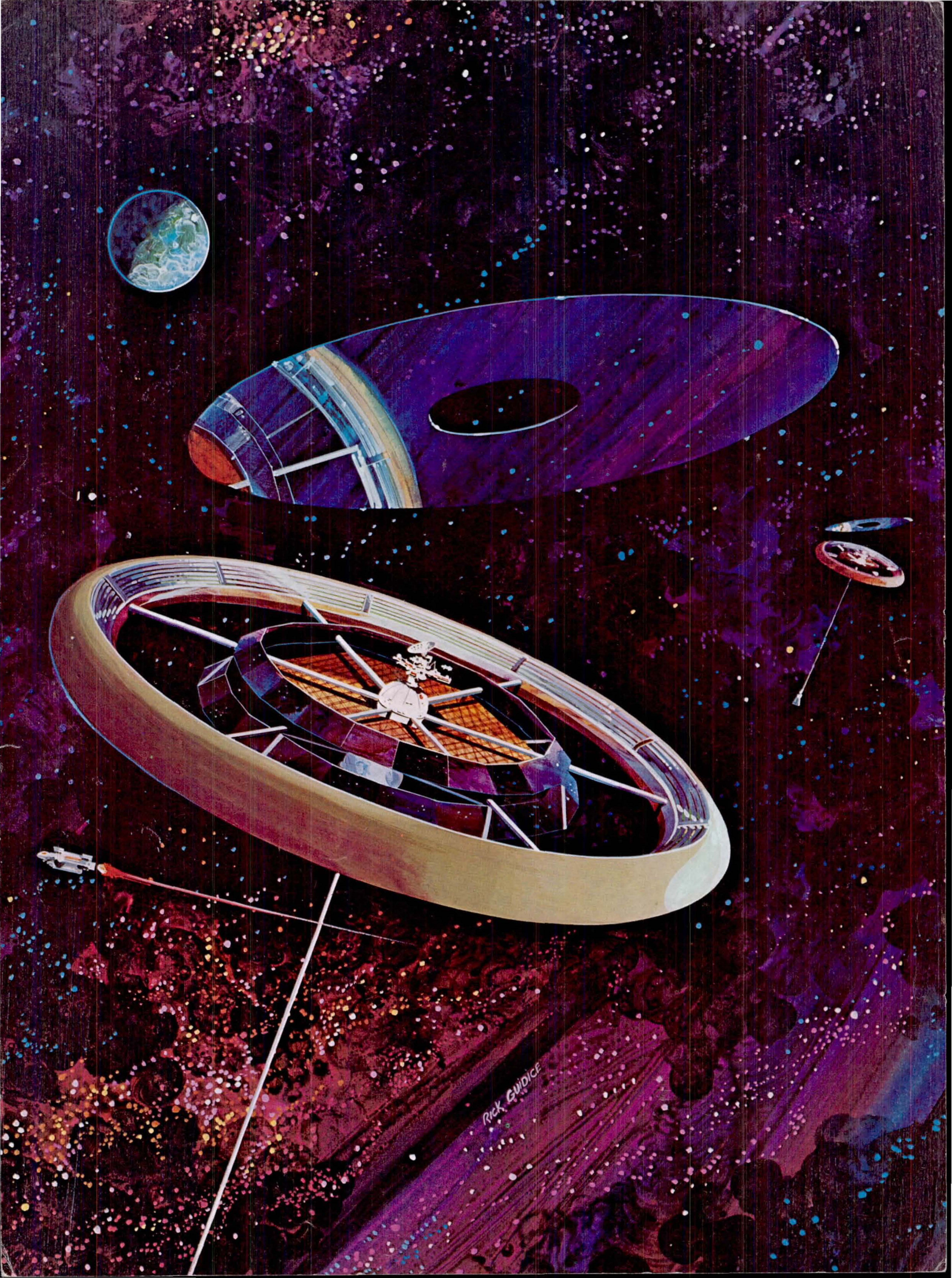
RICK GUIDICE

1. The Colonization of Space

We have put men on the Moon. Can people live in space? Can permanent communities be built and inhabited off the Earth? Not long ago these questions would have been dismissed as science fiction, as fantasy or, at best as the wishful thinking of men ahead of their times. Now they are asked seriously not only out of human curiosity, but also because circumstances of the times stimulate the thought that space colonization offers large potential benefits and hopes to an increasingly enclosed and circumscribed humanity.

Permanent communities can be built and inhabited off the Earth. The following chapters present a detailed description of a system for the colonization of space. It is not the best system that can be devised; nor is it complete. Not all the important questions about how and why to colonize space have been posed. Of those that have, not all have been answered satisfactorily. Nevertheless, the 10-week summer study is the most thorough and comprehensive one made to date. On its basis space colonization appears to be technically feasible, while the obstacles to further expansion of human frontiers in this way are principally philosophical, political, and social rather than technological.

THE OVERALL SYSTEM

The focus of the system is a space habitat where 10,000 people work, raise families, and live out normal human lives. Figure 1-1 shows the wheel-like structure in which they live. This structure orbits the Earth in the same orbit as the Moon in a stable position that is equidistant from both Earth and Moon. This is called the Lagrangian libration point, L_5. The habitat consists of a tube 130 m (427 ft) in diametral cross section bent into a wheel 1790 m (over 1 mi) in diameter. The people live in the ring-shaped tube which is connected by six large access routes (spokes) to a central hub where incoming spacecraft dock. These spokes are 15 m (48 ft) in diameter and provide entry and exit to the living and agricultural areas in the tubular region. To simulate Earth's normal gravity the entire habitat rotates at one revolution per minute about the central hub.

Much of the interior of the habitat is illuminated with natural sunshine. The Sun's rays in space are deflected by a large stationary mirror suspended directly over the hub. This mirror is inclined at 45° to the axis of rotation and directs the light onto another set of mirrors which, in turn, reflect it into the interior of the habitat's tube through a set of louvered mirrors designed to admit light to the colony while acting as a baffle to stop cosmic radiation. With the help of abundant natural sunshine and controlled agriculture, the colonists are able to raise enough food for themselves on only 63 ha (156 acres). The large paddle-like structure below the hub is a radiator by which waste heat is carried away from the habitat.

Abundant solar energy and large amounts of matter from the Moon are keys to successfully establishing a community in space. Not only does the sunshine foster agriculture of unusual productivity, but also it provides energy for industries needed by the colony. Using solar energy to generate electricity and to power solar furnaces the colonists refine aluminum, titanium, and silicon from lunar ores shipped inexpensively into space. With these materials they are able to manufacture satellite solar power stations and new colonies. The power stations are placed in orbit around the Earth to which they deliver copious and valuable electrical energy. The economic value of these power stations will go far to justify the existence of the colony and the construction of more colonies.

Principal components of the overall space colonization system and their interrelations are shown schematically in figure 1-2.

DESIGN GOALS

This system is intended to meet a set of specific design goals established to guide the choice of the principal elements of a practicable colony in space. The main goal is to design a permanent community in space that is sufficiently productive to maintain itself, and to exploit actively the environment of space to an extent that permits growth, replication, and the eventual creation of much larger communities. This initial community is to be a first step in an expanding colonization of space.

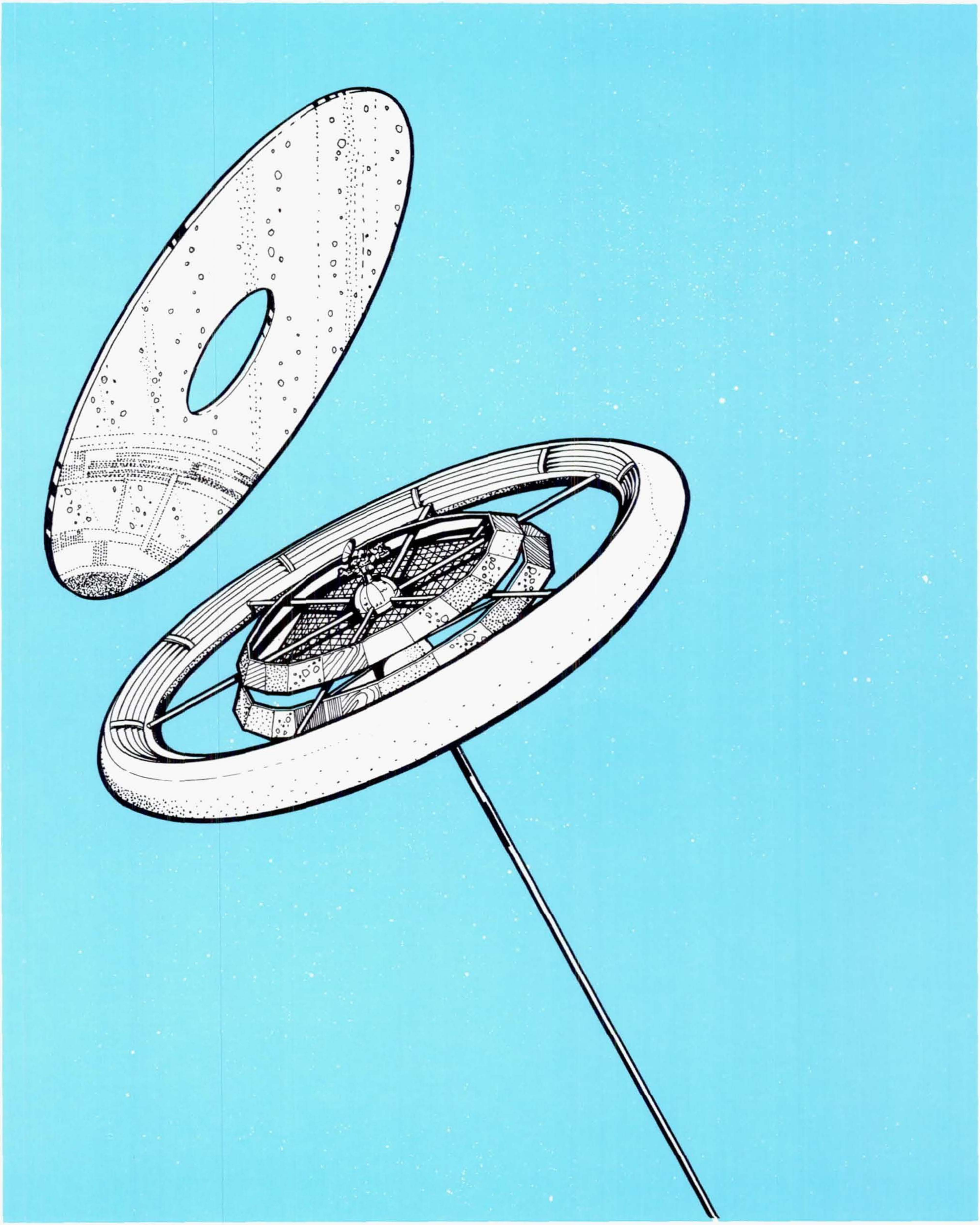

Figure 1-1. *The colony at Lagrangian point L_5.*

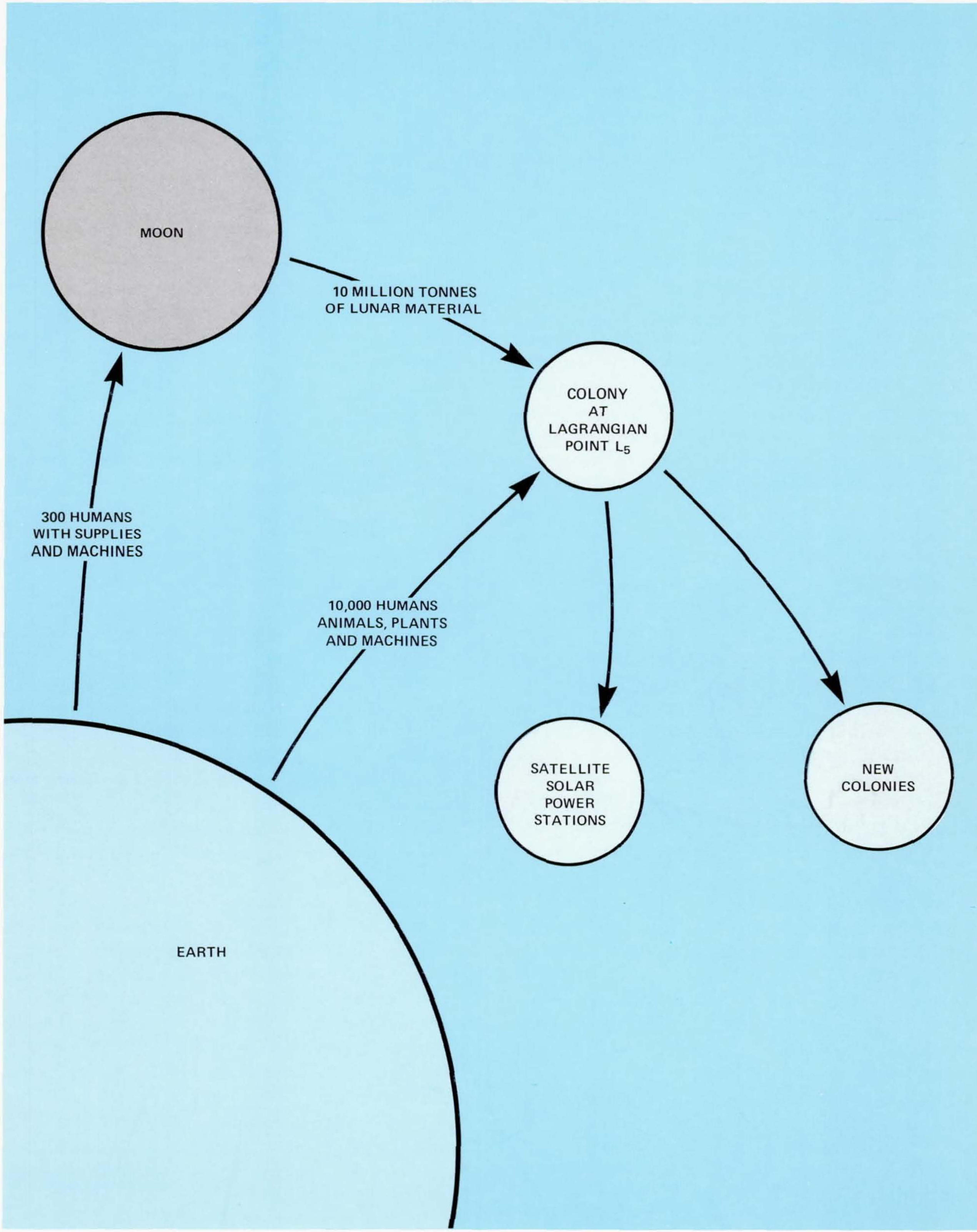

Figure 1-2. *The space colonization system.*

To effect this main goal, the following subsidiary goals must be met using existing technology and at minimum cost:

1. Design a habitat to meet all the physiological requirements of a permanent population and to foster a viable social community.

2. Obtain an adequate supply of raw materials and provide the capability to process them.

3. Provide an adequate transport system to carry people, raw materials, and items of trade.

4. Develop commercial activity sufficient to attract capital and to produce goods and services for trade with Earth.

Fortunately, the design study could draw on substantial earlier work. Active interest in space colonization as a practical possibility began in 1969 when Gerard O'Neill and students at Princeton University undertook a detailed assessment of space colonization. They aimed at a model to show the feasibility of a space colony rather than an optimum configuration and they selected as a test case a rotating habitat in satellite orbit around the Earth at the distance of the Moon, using solar energy to sustain a closed ecological system. They proposed a habitat constructed of processed lunar ore delivered by an electromagnetic accelerator and located at either the Lagrangian point L_4 or L_5 in order to make delivery of the ore as simple as possible. (The Lagrangian points are described in ch. 2.) The habitas was configured as a 1-km long cylinder with hemispherical end-caps. It was to have an Earth-like internal environment on the inner surface and be supplied with sunlight reflected from mirrors (ref. 1).

Subsequently, the Princeton group suggested that the L_5 colony could construct solar power stations from lunar material. They concluded that this would improve the economics of both the satellite solar power stations and the colony itself (ref. 2).

The concept of satellite solar power stations has received increasing attention since its introduction by Peter Glaser in 1968 (ref. 3).

These ideas were further considered and developed by a conference "Space Manufacturing Facilities" which took place at Princeton University on May 7-9, 1975 and focused more attention on O'Neill's test case.

This report presents a rationale for the design choices of the Ames-Stanford study group and it details how the various parts of the system interrelate and support each other. The next three chapters discuss successively how the properties of space specify the criteria that a successful design must satisfy, what human needs must be met if people are to live in space, and the characteristics of various alternative components of the design. Some readers may wish to skip directly to chapter 5 where the details of the operation of the system are described. Chapter 6 provides a detailed analysis of the sequence of events needed for the colony to be built. Timetables, manpower requirements, and levels of funding are presented for the construction of the main parts of the overall system. This chapter also looks at long-term benefits from solar power stations in space and some possible ways to structure economics so as to initiate the establishment and growth of many colonies over the long term. Chapter 7 looks at the future development of colonization of space, and finally chapter 8 discusses why space colonization may be desirable and provides some conclusions and recommendations for further activities and research.

THE HISTORY OF AN IDEA

The history of the idea of space colonization extends back into myths and legends of ancient times, but the first account of an actual space colony appeared in 1869 when Edward Everett Hale's novel, Brick Moon, described how a colony in space happened by accident.

A brick sphere, intended for guiding maritime navigators, was to be catapulted into Earth orbit by rotating wheels. When it rolled onto the catapult too soon, still containing many workers inside, the first space colony was launched. Fortunately, the workers had ample food and supplies (even a few hens), and they decided to live the good life permanently in space, maintaining contact with the Earth only by a Morse code signalled by making small and large jumps from the external surface of their tiny spherical brick colony (ref. 4).

The following quotation on the history of the idea of space colonization is taken with permission directly from "Space Colonization Now?" by Robert Salkeld, Astronautics and Aeronautics, September, 1975.

"Precursors of the notion of small self-contained worlds in space appeared in novels by Jules Verne in 1878 and Kurd Lasswitz in 1897 (refs. 5,6).

"In 1895 the space-station concept was noted from a more technical viewpoint in a science-fiction story by Konstantin Tsiolkovsky (ref. 7). In 1903 Tsiolkovsky expanded his description of the manned space station to include rotation for artificial gravity, use of solar energy, and even a space "greenhouse" with a closed ecological system (ref. 8). Thus, at the turn of the Twentieth Century, the idea of the space habitat was defined in terms of some of its basic elements.

"The idea progressed slowly over the next fifty years, then accelerated. In 1923 Hermann Oberth elaborated on potential uses of space stations, noting that they could serve as platforms for scientific research, astronomical observations, and Earth-watch (ref. 9). In 1928 Guido von Pirquet considered a system of three stations, one in a near orbit, one more distant, and a transit station in an intermediate elliptical orbit to link the other two; he suggested that they might serve as refueling depots for deep space flights (ref. 10). The concept of a rotating wheel-shaped station was introduced in 1929 by Potočnik, writing as Hermann Noordung. He called his 30-m-diam station "Wohnrad" (living wheel)[1] and suggested that it be placed in geosynchronous[2] orbit (ref. 11). During World War II, space stations received some military study in Germany (ref. 12), and after the war the idea surfaced again in technical circles as a geosynchronous rotating-boom concept[3] proposed by H. E. Ross in 1949 (ref. 13).

"The space-station idea was popularized in the United States by Wernher von Braun. In 1952 he updated Noordung's wheel, increased the diameter to 76 m, and suggested a 1730-km orbit (ref. 14). At about the same time, Arthur C. Clarke published "Islands in the Sky," a novel involving larger stations (ref. 15), and in 1961 Clarke (in another novel) suggested placing large stations at the Lagrangian libration points where they would maintain a fixed position relative to both the Earth and the Moon (ref. 16). In 1956 Darrell Romick advanced a more ambitious proposal – for a cylinder 1 km long and 300 m in diameter with hemispherical end-caps having a 500-m-diam rotating disc at one end to be inhabited by 20,000 people (ref. 17).

"The companion idea of a nuclear-propelled space ark carrying civilization from a dying solar system toward another star for a new beginning was envisioned in 1918 by Robert Goddard. Possibly concerned about professional criticism, he placed his manuscript in a sealed envelope for posterity and it did not see print for over half a century (ref. 18). In 1929 the concepts of artificial planets and self-contained worlds appeared in the works of J. D. Bernal and Olaf Stapledon, and by 1941 the interstellar ark concept had been fully expanded by Robert A. Heinlein and others, many appearing in the science-fiction publications of Hugo Gernsback and others (refs. 19-24). In 1952 the concept was outlined in more technical detail by L. R. Shepherd (ref. 25), who envisioned a nuclear-propelled million-ton interstellar colony shaped as an oblate spheroid, which he called a "Noah's Ark."

"A related idea, the use of extraterrestrial resources to manufacture propellants and structure, was suggested by Goddard in 1920. It became a common theme in science fiction and reappeared in technical literature after World War II. In 1950 A. C. Clarke noted the possibility of mining the Moon and of launching lunar material to space by an electromagnetic accelerator along a track on its surface (ref. 26).

"In 1948 Fritz Zwicky suggested use of extraterrestrial resources to reconstruct the entire universe, beginning with making the planets, satellites, and asteroids habitable by changing them intrinsically and changing their positions relative to the Sun (ref. 27). A scheme to make Venus habitable by injecting colonies of algae to reduce atmospheric CO_2 concentration was proposed in 1961 by Carl Sagan (ref. 28). In 1963 Dandridge Cole suggested hollowing out an ellipsoidal asteroid about 30 km long, rotating it about the major axis to simulate gravity, reflecting sunlight inside with mirrors, and creating on the inner shell a pastoral setting as a permanent habitat for a colony (ref. 29).

"In 1960 Freeman Dyson suggested an ultimate result of such planetary engineering (ref. 30); processing the materials of uninhabited planets and satellites to fashion many habitats in heliocentric orbits. A shell-like accumulation of myriads of such habitats in their orbits has been called a Dyson sphere."

On July 20, 1969 Astronauts Neil A. Armstrong and Edwin E. Aldrin, Jr., walked on the Moon. In the context of history just reviewed the ". . . one small step for a man, one giant leap for mankind" appears quite natural and unsurprising. And if the first step is to be followed by others, space colonization may well be those succeeding steps. Perhaps mankind will make the purpose of the next century in space what Hermann Oberth proposed several decades ago:

"To make available for life every place where life is possible. To make inhabitable all worlds as yet uninhabitable, and all life purposeful."

[1] Noordung's concept was of a three unit space colony: the living wheel (Wohnrad), the machine station (Maschinenhaus), and the observatory (Observatorium): Ed.

[2] A satellite in geosynchronous orbit revolves around the Earth in the same period that Earth rotates on its axis: Ed.

[3] Actually a rotating living section with a nonrotating boom for linkage to space shuttle craft: Ed.

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[4]The remainder of the references for this chapter, i.e., 5 through 29, is as cited by Salkeld, R.; Space Colonization Now? Astronautics and Aeronautics, vol. 13, no. 9, Sept. 1975, pp. 30-34.

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2. Physical Properties of Space

The physical properties of space are rich in paradoxes. Space seems empty but contains valuable resources of energy and matter and dangerous fluxes of radiation. Space seems featureless but has hills and valleys of gravitation. Space is harsh and lifeless but offers opportunities for life beyond those of Earth. In space, travel is sometimes easier between places far apart than between places close together.

The purpose of this chapter is to explore and understand these properties of space and the apparent paradoxes to derive a set of basic design criteria for meeting the goals for space colonization set out in chapter 1. Together with considerations of the physiological and psychological needs of humans in space, these basic criteria compose the quantitative and qualitative standards on which the design of the space colonization system is based. These criteria also serve as the basis for a discussion and comparison of various alternative ways to locate, organize and construct, and interconnect the mines, factories, farms, homes, markets, and businesses of a colony in space.

THE TOPOGRAPHY OF SPACE

For the resources of space to be tapped safely, conveniently and with minimum drain on the productive capabilities of the colonists and Earth, the peculiarities of the configuration of space must be understood.

Planets and Moons: Deep Gravity Valleys

Gravitation gives a shape to apparently featureless space; it produces hills and valleys as important to prospective settlers in space as any shape of earthly terrain was to terrestrial settlers. In terms of the work that must be done to escape into space from its surface, each massive body, such as the Earth and the Moon, sits at the bottom of a completely encircled gravitational valley. The more massive the body, the deeper is this valley or well. The Earth's well is 22 times deeper than that of the Moon. Matter can be more easily lifted into space from the Moon than from the Earth, and this fact will be of considerable importance to colonists in deciding from where to get their resources.

Libration Points: Shallow Gravity Wells

There are other shapings of space by gravity more subtle than the deep wells surrounding each planetary object. For example, in the space of the Earth-Moon system there are shallow valleys around what are known as Lagrangian libration points (refs. 1,2). There are five of these points as shown in figure 2-1, and they arise

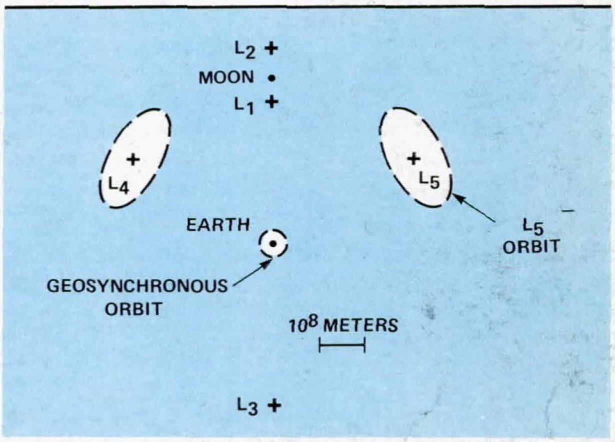

Figure 2-1.– *Earth-Moon libration points.*

from a balancing of the gravitational attractions of the Earth and Moon with the centrifugal force that an observer in the rotating coordinate system of the Earth and Moon would feel. The principal feature of these locations in space is that a material body placed there will maintain a fixed relation with respect to the Earth and Moon as the entire system revolves about the Sun.

The points labeled L_1, L_2, and L_3 in figure 2-1 are saddle-shaped valleys such that if a body is displaced perpendicularly to the Earth-Moon axis it slides back toward the axis, but if it is displaced along the axis it moves away from the libration point indefinitely. For this reason these are known as points of unstable equilibrium. L_4 and L_5 on the other hand represent bowl-shaped valleys, and a body displaced in any direction returns toward the point. Hence, these are known as points of stable equilibrium. They are located on the Moon's orbit at equal distances from both the Earth and Moon.

The foregoing picture is somewhat oversimplified; it neglects the effect of the Sun. When this is taken into consideration (refs. 3,4), stable equilibrium is shown to be possible only in particular orbits around L_4 and L_5, as indicated by the dashed lines in figure 2-1. The shape of space around L_4 and L_5 is discussed in detail in reference 4. The basic conclusion is that massive objects placed in the vicinity of L_4 and L_5 would orbit these points with a period of about one month while accompanying the Earth and Moon around the Sun. At the price of the expenditure of some propulsive mass, objects could be maintained near the other libration points rather easily (ref. 5). The cost of such station keeping needs to be better understood before the usefulness of these other points for space colonies can be evaluated.

Two Kinds of Separation in Space: Metric Distance vs Total Velocity Change (Δv)

The availability of resources for use by colonists is closely related to the properties of space. The colony should be located where station-keeping costs are low, where resources can be shipped in and out with little expenditure of propulsion mass, and where the time required to transport resources and people is short. These three criteria, minimum stationkeeping, minimum propulsion cost, and minimum transportation time cannot be satisfied together. Some balance among them is necessary. In particular, time and effort of transportation are inversely related.

Figure 2-1 shows the distances between points in the vicinity of Earth of importance to space colonization. The diagram is to scale, and the distances are roughly in proportion to time required to travel between any two points. However, in space travel the important measure of propulsive effort required to get from one point to another is the total change in velocity required (Δv). Thus the Δv to go from low Earth orbit (an orbit just above the atmosphere) to lunar orbit is 4100 m/s, which is only 300 m/s more than to go to geosynchronous orbit (note that these numbers are not additive). Figure 2-2 shows a schematic diagram of the Δv's required to move from one point to another. It is drawn to scale with respect to Δv, and shows that most of the effort of space travel near the Earth is spent in getting 100 km or so off the Earth, that is, into low Earth orbit. Note, this orbit is so close to the Earth's surface that it does not show on the scale of figure 2-1. Thus travel time to low Earth orbit is a few minutes, but the effort required to obtain this orbit is very large. Or, again revealing the inverse relation between travel time and effort, to go from low Earth orbit to lunar orbit takes about 5 days, but requires less than half the effort needed to go from the Earth's surface to low orbit. Figure 2-2 also shows that certain points that are far apart in distance (and time) are quite close together in terms of the propulsive effort required to move from one to the other; for example, geosynchronous orbit, L_5, and lunar orbit.

The three primary criteria for choosing sites for the various parts of the colony – mines, factories, farms, homes, markets – are ease of access to needed resources, rapidity of communication and transportation and low cost. The topography of space can be exploited to achieve satisfactory balances among them.

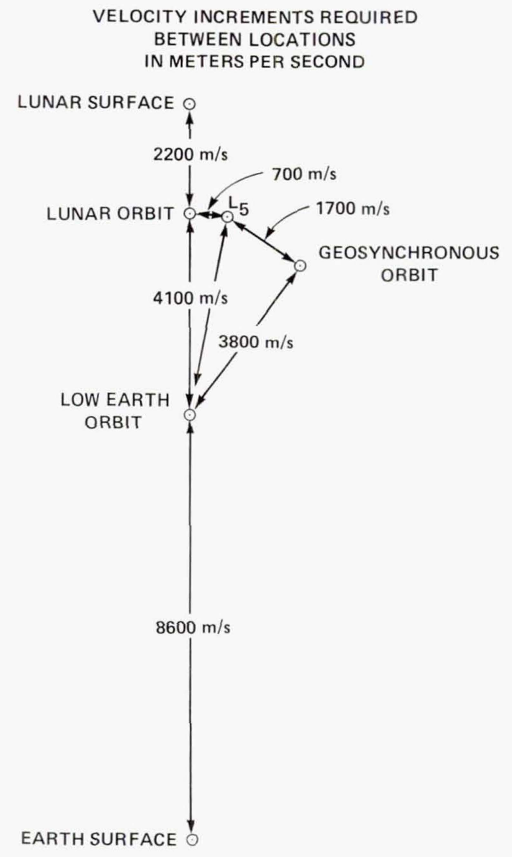

Figure 2-2.– *Velocity increments to transfer between points in space.*

SOLAR RADIATION: AN ABUNDANT AND ESSENTIAL SOURCE OF ENERGY

Although apparently empty, space is in fact filled with radiant energy. Beyond Earth's atmosphere this energy flows more steadily and more intensely from the Sun than that which penetrates to the surface of the Earth. Through one square meter of space facing the Sun pass 1390 W of sunlight; this is nearly twice the maximum of 747 W striking a square meter normal to the Sun at the Earth's surface. Since the Earth does not view the Sun perpendicularly and is dark for half of each day, a square meter of space receives almost 7.5 times the sunlight received by an average square meter on the whole of the Earth. Figure 2-3 compares the wavelength distribution of the Sun's energy as seen from above the Earth's atmosphere with that seen at the surface of the Earth and shows that not only is the intensity of sunlight greater in space, but also there are available in space many wavelengths that are filtered out by the Earth's atmosphere.

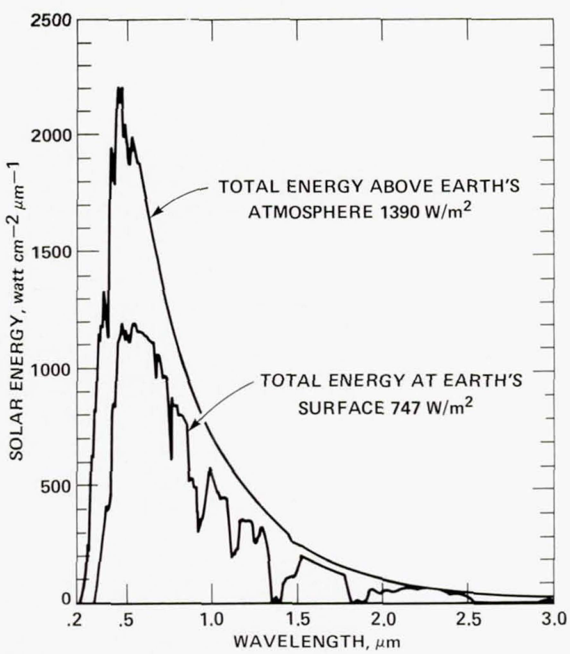

Figure 2-3.– *Solar radiation as a function of wavelength.*

To live in space humans must be protected from the fierce intensity and penetrating wavelengths of unattenuated sunlight, but this same energy is one of the primary resources of space. If this steady, ceaseless flux of solar energy is tapped its value may be very large. If the Sun's energy is converted with 10 percent efficiency to electrical power which is sold at a rate of \$.012/kW-hr, a square kilometer of space would return more than \$14,000,000 each year.

It is important for the colonization of space that an effective way be found to use this solar energy.

MATTER IN SPACE: A MAJOR RESOURCE

Space is extraordinarily empty of matter. The vacuum of space is better than any obtainable with the most refined laboratory equipment on Earth. This vacuum may be a resource in its own right, permitting industrial processes impossible on Earth. Nevertheless, there is matter in space and it is of great interest to space colonization.

Matter in space comes in a broad spectrum of sizes great masses that are the planets and their satellites, smaller masses that are the asteroids, even smaller meteoroids, and interplanetary dust and submicroscopic particles of ionizing radiation. The entire range is of interest to space colonization because the principal material resources must come from the great masses while meteoroids and ionizing radiation may be dangerous to the colony's inhabitants.

Sources of Matter in Space

The principal material resources of space are the planets, their moons, and asteroids. Their accessibility is determined by distance from possible users of the material and by the depth of the gravitational wells through which the matter must be lifted.

The planets of the solar system are major loci of material resources, but they are mostly very distant from prospective colonies, and all sit at the bottoms of deep gravitational wells. The effort to haul material off the planets is so great as to make the other sources seem more attractive. Of course, if a planet is nearby and is rich in resources, a colony might find the effort justified. Consequently, the Earth could be an important source of material to a colony in its vicinity, especially of the elements hydrogen, carbon, and nitrogen that are not available in sufficient amounts elsewhere near Earth.

The moons of planets, with their usually shallow gravitational wells, offer an attractive source of needed matter. The moons of Mars have very shallow wells, but they are too distant from any likely initial site for a colony to be useful. The same argument applies even more strongly to the more distant satellites of the outer planets. It is the Earth's natural satellite, the Moon, that offers an attractive prospect. The Moon is near the likely initial sites for a space colony; its gravitational well is only 1/22 as deep as that of the Earth. Moreover, as figure 2-4 shows, the Moon can be a source of light metals, aluminum, titanium, and iron for construction, oxygen for respiration and rocket fuel, and silicon for glass (ref. 6). There are also trace amounts of hydrogen

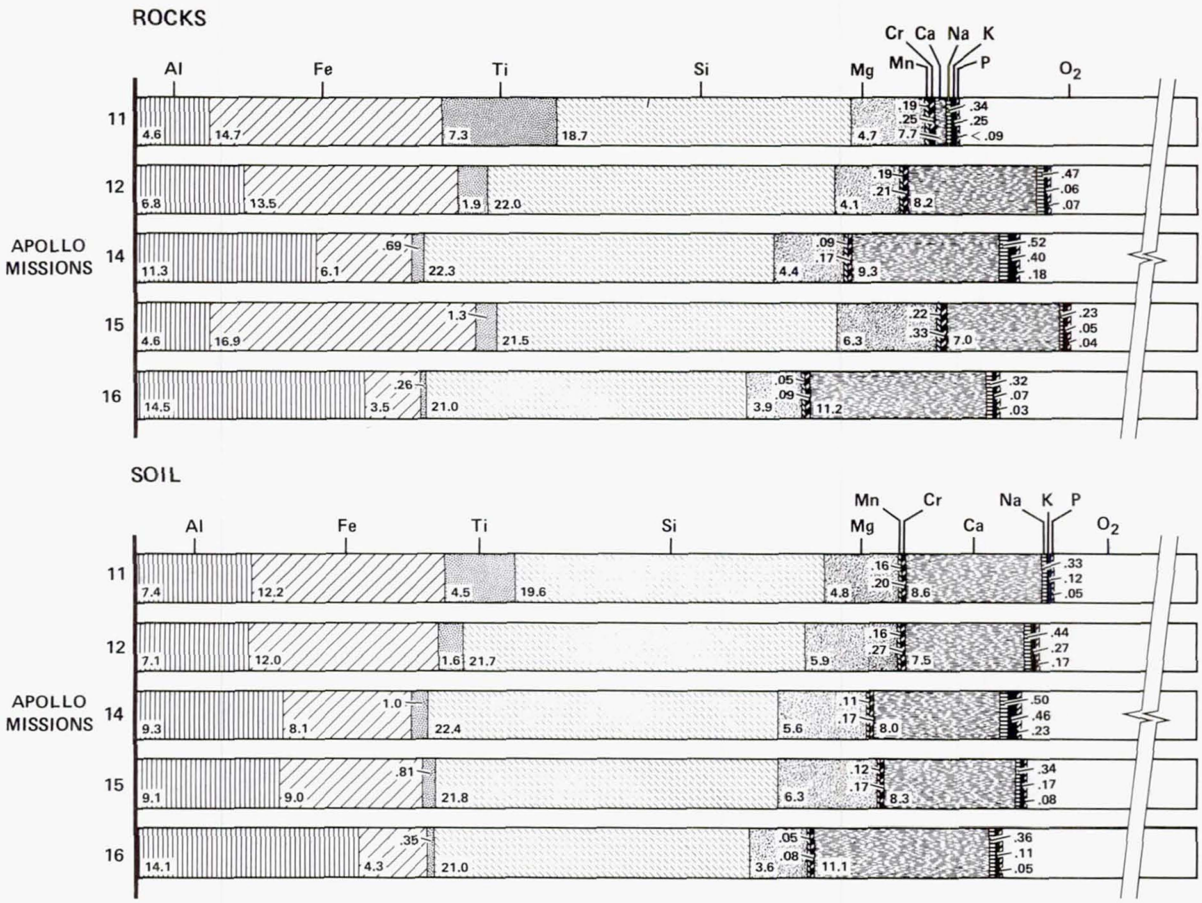

Figure 2-4. – *Average compositions of rocks and soil returned by Apollo missions, excluding oxygen (≈ 45%) and elements present in amounts less than 1000 ppm.*

(40 ppm) and carbon on the Moon, but not enough to supply a colony. Certainly the Moon's resources, supplemented with small amounts of particular elements from Earth, can supply all the elements necessary to sustain human life and technology in a space colony.

Asteroids offer some interesting possibilities. They have very shallow gravitational wells; some come closer to Earth than Mars; and some asteroids may contain appreciable amounts of hydrogen, carbon, and nitrogen as well as other useful minerals (refs. 7-14). Moving in well determined orbits which could be reached relatively easily, the asteroids may become exceptionally valuable resources, especially those that contain appreciable amounts of water ice and carbonaceous chondrite.

Comets may also be included in this inventory of material resources of space. Like many meteoroids, comets are thought to be "dirty snowballs," a conglomerate of dust bound together with frozen gases and ice. Comets are not suitable resources because of their high velocity and their infrequent penetration of the inner Solar System.

Meteoroids: An Insignificant Danger

Measurements made on Earth, in space, and on the Moon (refs. 8,10,11,13) have provided a fairly complete picture of the composition, distribution, and frequency of meteoroids in space. Near the Earth most of these travel relative to the Sun with a velocity of about 40 km/s. Figure 2-5 plots the frequency of meteoroids exceeding a given mass versus the mass, that is, it gives an integral flux. This graph shows that on the average a given square kilometer of space will be traversed by a meteoroid with a mass of 1 g or greater about once every 10 years, and by one with mass of 100 g or greater about once in 5000 years. A 10-kg meteoroid might be expected once every 100,000 years.

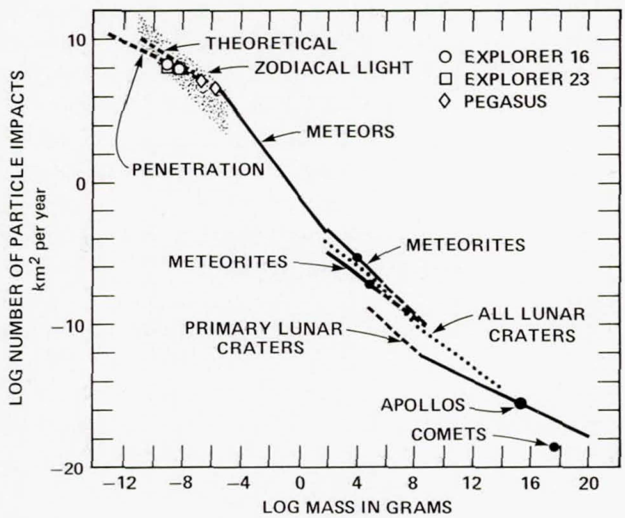

Figure 2-5. – *Impact rates of meteoritic material.*

Danger of collision of a large meteoroid with a space habitat seems remote. But meteoroids occur frequently in clusters or showers, so that when one collision is likely, so are several more. There is a possibility of a correlated sequence of collisions with attendant damage more serious and complicated than from a single collision. This form of risk would only occur on a time scale of hundreds of years, which is the time scale characteristic of the occurrence of showers of meteoroids.

Although the probability of severe structural damage from impact of a meteoroid is negligible, blast effects of even a small meteoroid could be serious. Impact of a meteoroid with a closed vessel, for example, a spaceship or habitat, will produce a pressure wave which although quite localized will be dangerous to anyone near its origin. A one gram meteoroid, if it lost all its energy by striking a vessel, might kill or seriously harm someone standing close to the point of collision, but would be harmless to anyone more than a few meters away. Clearly it is desirable to shield a space colony against such collisions, and as is discussed subsequently, extensive shielding is also required for protection against ionizing radiation. This radiation shield would also protect against meteoroids.

Loss of atmosphere because of puncture by meteoroids is not a serious threat. In habitats of the size considered in this study, at least a day would be required to lose 60 percent of the atmosphere through a hole one meter in diameter – the size of hole that would be blasted by a meteoroid only once in 10,000,000 years. Smaller meteoroids might be responsible for small leaks, but the requirement for safe habitation under these circumstances is simply a regular (*e.g.*, monthly) program for detecting and repairing such leaks. A more detailed analysis of the meteoroid hazard is given in appendix A.

Ionizing Radiation: Major Threat

Both the Sun and the Galaxy contribute fluxes of ionizing particles. The quiescent Sun constantly emits a solar wind (ref. 15) of about 5 to 10 protons, electrons, and particles per cubic centimeter traveling at speeds of about 500 km/s. These particles do not possess penetrating energies and therefore offer no threat to humans. However, the solar wind may indirectly affect humans because it neutralizes any separation of electric charge that might occur in space and produces a small variable interplanetary magnetic field ($\sim$5 nT at the distance of the Earth (1AU) from the Sun). Consequently, space contains essentially no electric field, whereas on Earth the electric field is 100 V/m near the surface. Given that the human body is a good electrical conductor and forms an equipotential surface in the Earth's field, and that humans live a good portion of their lives in electrostatically shielded buildings, it seems unlikely that living for prolonged times in the absence of an electric field would cause harm, but this is not definitely known. Similarly, although there is evidence that living in magnetic fields thousands of times more intense than the Earth's will harm people, the consequences of living in a magnetic field that is both 10,000 times weaker and variable with time are not known (refs. 16,17).

Solar flares and galactic cosmic rays on the other hand are direct and serious threats to life in space. In sporadic violent eruptions the Sun emits blasts of high energy protons capable of delivering dangerous doses of radiation. Figure 2-6 shows the integral flux of solar flare particles at the Earth's distance from the Sun and compares it with the galactic flux. For these moderate sized events the galactic flux is the dominant source of particles above 1 GeV/nucleon. Also shown in figure 2-6 is the most intense flare ever recorded (a class 4 solar flare) which occurred on February 23, 1956. This flare illustrates the worst known radiation conditions to be expected in space. Without a space habitat having extensive protection against extremely energetic protons such a flare would contribute many tens of rem of dose in less than an hour to moderately shielded personnel, and many times the fatal dose to the unprotected human being. (For an explanation of the "rem" see appendix B.)

The frequency of dangerous cosmic-ray flares is once in several years during a solar maximum, and once in a few decades for a flare as large as the class 4 flare. Because a significant portion of the protons originating from a large flare are relativistic (i.e., traveling at speeds approaching that of light), there is only a few minutes between optical and radio indications of an outburst and the arrival of the peak of the proton flux. People not in a sheltered place have very little time to get to one. Once a flare has begun, fluxes of energetic particles persist for a day or so in all directions.

Cosmic rays from the galaxy are a continuous source of highly penetrating ionizing radiation. Figure 2-7 shows the galactic cosmic ray spectrum and chemical abundances. The lower-energy portions of the curves show the modulating effect of the solar wind which with varying effectiveness over the 11-year solar cycle sweeps away from the Sun the less penetrating particles of the galactic cosmic rays. In the absence of any shielding the galactic cosmic radiation would deliver an annual dose of about 10 rem.

An important feature of note in figure 2-7 is the presence of heavy nuclei such as iron. In fact, heavy cosmic ray nuclei range up to heavy transuranium elements but quite noticeably peaking in abundance around iron. When a fully ionized iron nucleus is traveling below about half the speed of light its ionizing power is several thousand times that of minimally ionizing protons. (See appendix B for a brief discussion of the behavior of charged particles in matter.) At this level of ionizing power the passage of a single iron nucleus through the human body destroys an entire column of cells along its trajectory. The total amount of energy dumped in the body is small, but it is concentrated intensively over localized regions.

It is not yet known how bad this form of radiation is in terms of such things as increased rates of cancer. However, the loss of nonreproducing cells, such as spinal-column nerve cells, that any given exposure will

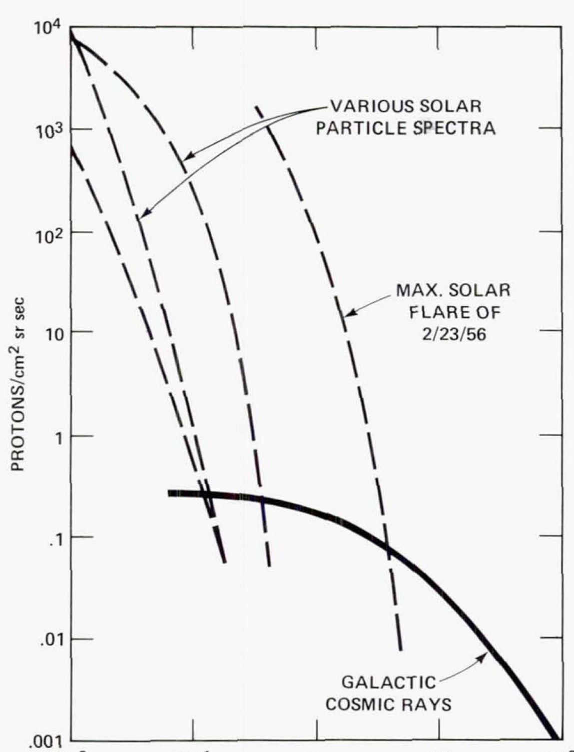

Figure 2-6.– *Energy spectra from several moderate size solar flares (dotted curves) compared with galactic cosmic ray spectrum.*

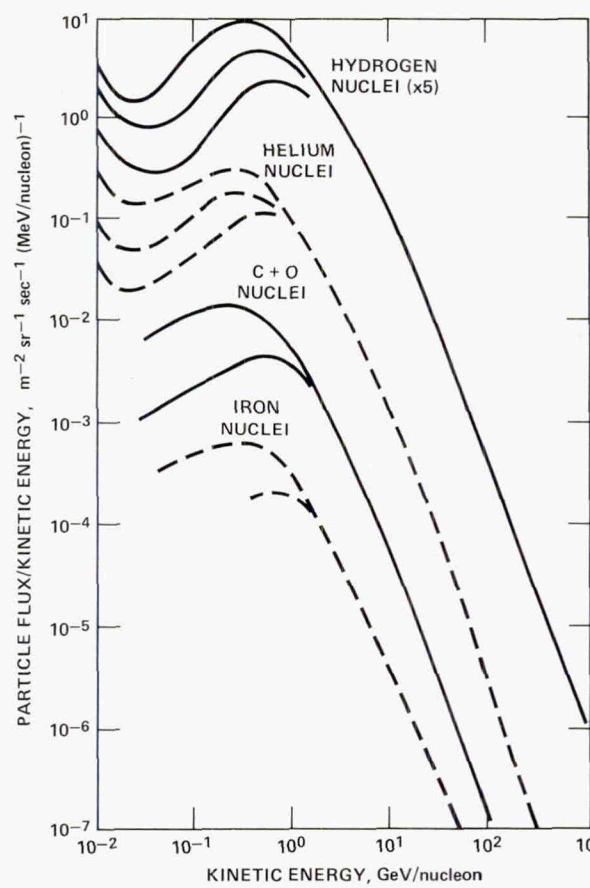

Figure 2-7.– *Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity. (Taken from* Physics Today, *Oct. 1974, p. 25.)*

cause can be calculated, Comstock *et al.* (ref. 18) estimate that the Apollo 12 astronauts during their two week voyage lost between 10^{-7} and 10^{-4} of their non-replaceable cells. Such losses, although negligible in adults, might be very serious in developing organisms such as children.

The phenomenon of secondary particle production is important. When high-energy particles collide with matter, in a shield for example, they produce a great spray of particles, which in turn may produce even more particles. Consequently, the addition of a little shielding may, in the presence of highly energetic particles like those at the upper end of the cosmic ray spectrum, give rise to an even larger radiation dosage than if no shielding were used. There is also the possibility that a little shielding will slow down the rapidly moving heavy ions and make them more effective in the damage they do to tissue. Thus, for shielding that has a mass of a few tonnes[1] for each square meter of surface protected the effect will be to increase the annual dosage from cosmic rays from about 10 rem to as much as 20 rem.

But what is an acceptable radiation dose? For the terrestrial environment the U.S. Federal Government sets two standards (refs. 19-21). For radiation workers, adults over the age of eighteen working in industries where exposure to radiation is apt to occur, the standard is 5 rem/yr. For the general population, and especially children and developing fetuses, the standard is less than 0.5 rem/yr. Arguments can be sustained that these limits are conservative. There is evidence that exposures to steady levels of radiation that produce up to 50 rem/yr will result in no detectable damage (refs. 20,21), but the evidence is not fully understood nor are the consequences known of long-term exposure at these levels. For comparison, most places on Earth have a background of about 0.1 rem/yr.

APPENDIX A

METEOROIDS AND SPACE HABITATS

The risk of damage by collision with meteoroids can be assessed if the flux of meteoroids as a function of mass values can be determined. Data to do this come from three sources:

1. Photographic and radar observations from the Earth of meteors entering the atmosphere,
2. Measurements from spacecraft of meteoroid fluxes,
3. Lunar impacts measured by lunar seismometers.

In the meteoroid mass range from 10^{-6} to 1 g spacecraft sensors provide abundant data, and for masses above 10 kg the lunar seismic network is believed to be 100 percent efficient in assessing the flux.

Earth based data are subject to large corrections but agree with space data at the 10-g value.

Figure 2-5 shows the distribution law (integral flux) for meteoroid masses of interest to the problem of habitat protection. The Prairie Network data are not shown because they are subject to large corrections of an uncertain nature. The type of meteoroid structure most commonly found in space is a conglomerate of dust bound together by frozen gases. This has been described as a "dirty snowball" as opposed to a stoney or nickel-iron rock that remains at the Earth's surface after a meteorite survives passage through the atmosphere.

The hazard of meteors is not necessarily that of a single collision. Because meteors occasionally occur in clusters or "showers," they could, by a series of hits, initiate a chain of failures otherwise impossible.

On an average night an observer will see about 10 meteors an hour. During the most intense of annual showers the observation rate rises to about 50 an hour. Thus the existence of annual showers causes temporary flux enhancements by perhaps a factor of 5. In the year 1833 the hourly rate over Paris from the shower of Leonids rose to 35,000 an hour – an increase in flux of many thousand times. Thus the meteoroid flux can at times increase enormously to constitute a qualitatively different kind of hazard from the usual situation. A detailed analysis of what risk such a shower would entail must await a final system model for space habitation and extensive computer simulation. Even so it is apparent that the risk from showers would only occur on a time scale of hundreds of years.

The second piece of knowledge needed to assess meteoroid risk to space habitation is the damage caused by a meteoroid of a given size. There are three mechanisms of destruction. First, a mass traveling at the typical meteoroid velocity of 40 km/s will create a crater in any material object with which it collides. McKinley (ref. 22) quotes Whipple to the effect that the depth of penetration is related to the incident energy by:

$$E = \frac{\pi \zeta \xi d^3}{9} \qquad (1)$$

E = energy (ergs)
d = penetration depth (cm)
ζ = density (g/cc)
ξ = heat of fusion (ergs/g)

[1] A metric ton, or tonne, is 10^6 g and equals 0.98 long tons and 1.10 short tons.

TABLE 2-1.– SCALE OF DAMAGE FROM COLLISIONS WITH METEOROIDS AS A FUNCTION OF METEOROID MASS

Mass of meteoroid, g	Occurrence/km^2, yr	Energy, J	Diameter of crater, m	R(2 atm), m	Damage (depends on habitat volume)
1	10	8.5×10^5	0.02	2.3	Loss of window panel, 1 percent/hr leakdown
100	2000	8.5×10^7	.09	11	10-hr leakdown to 40 percent of one atmosphere
1×10^6	1×10^8	8.5×10^{11}	2	230	Major structural damage

Whipple is also quoted as saying that a thin metal sheet a meter or so away from the main hull acts as a "meteor bumper" by vaporizing any incident meteoroid and thus minimizing blast loading on the hull through $1/r^2$ attenuation of the blast wave.

The second damage effect is shock wave destruction of interior structures if a meteoroid penetrates the main hull. Such an event is equivalent to creating an explosion at the point of entry with 200 g of TNT for every gram of meteoroid traveling at 40 km/s. The overpressure in Pa of a strong explosion shock wave is given roughly by

$$P_{over} = \frac{0.34\ E}{R^3} \qquad (2)$$

E = total energy released, J
R = distance from shock center, m

As a point of reference, as little as 5 psi (34.5 kPa) overpressure suffices to knock down buildings and kill an average human being.

The third effect of meteoroid impact is the loss of internal atmosphere through the hole created. The repairing of such a hole is not a difficult problem since air flows, though supersonic in the hole region, fall to gentle values a few hole diameters away. The main operational problem for a habitat is efficient detection and repair of any small holes that occur.

Table 2-1 presents the risk factors for a space habitat due to meteoroid impacts. In this table R(2atm) is the radius at which any shock wave created has two atmospheres of overpressure[2] – a high value for a "kill radius!"

Obviously the hazards of meteoroids pose little danger to kilometer-sized habitats.

APPENDIX B

IONIZING RADIATION IN SPACE

The principal ionizing radiations to be found in space are summarized in table 2-2. Ionizing radiation endangers humans because it is capable of breaking chemical bonds in tissue. The damaging power depends upon the amount of energy deposited per unit volume, the rapidity with which the energy is transferred, and its concentration along the track of the particle of radiation.

Radiation which deposits 100 ergs of energy[3] per g is said to deliver a dose of 1 rad. Because different forms

[2] 2 atmospheres overpressure = 202 kPa.

[3] The most commonly used unit to measure energy of radiation is the electron volt (eV). This very small unit is defined as equal to the energy imparted to a particle with unit electric charge when it is accelerated through a potential difference of 1 V, or 1.6×10^{-12} ergs. Because of the small value of this unit super multiples are more common – keV for 10^3 eV, MeV for 10^6 eV, and GeV for 10^9 eV.

TABLE 2-2.– IONIZING RADIATIONS IN SPACE

Name	Charge (Z)	RBE	Location
X-rays	0	1	Radiation belts, solar radiation and in the secondaries made by nuclear reactions, and by stopping electrons
Gamma rays	0	1	
Electrons			
1.0 MeV	1	1	Radiation belts
0.1 MeV	1	1.08	
Protons			
100 MeV	1	1 – 2	Cosmic rays, inner radiation belts, solar cosmic rays
1.5 MeV	1	8.5	
0.1 MeV	1	10	
Neutrons			
0.05 eV (thermal)	0	2.8	Produced by nuclear interactions; found near the planets and the Sun and other matter
.0001 MeV	0	2.2	
.005 MeV	0	2.4	
.02 MeV	0	5	
.5 MeV	0	10.2	
1.0 MeV	0	10.5	
10.0 MeV	0	6.4	
Alpha particles			
5.0 MeV	2	15	Cosmic rays
1.0 MeV	2	20	
Heavy primaries	$\geqslant 3$	(see text)	Cosmic rays

of radiation may deposit this energy at different rates and with different intensities along the track, the biological damage of a dose of 1 rad varies with the type of radiation. To correct for this effect the radiation dose in rads is multiplied by the "relative biological effectiveness" (RBE) of the particular kind of radiation. The product is then a measure of danger of the particular kind of radiation, and that product is described in units of rems. Thus, 1 rem of neutrons and 1 rem of X-rays represent the same amount of biological danger. (For X-rays 1 rem results from the exposure of 1 roentgen.) The RBEs of most of the common kinds of radiation are given in the table.

The damaging power of heavy charged particles with charge numbers equal to or greater than 3 is most conveniently described in terms of their ionizing power. This measures how many chemical bonds per unit of body mass are broken and thereby gives a rough measure of the tissue damage sustained.

Figure 2-8 plots the ionizing power of protons in silicon dioxide as a function of proton energy. Since the units of ionizing power are in units of mass traversed, the same values are reasonably accurate for all matter with a low charge number (Z), for example, human tissue. This basic curve holds for any ion species when the vertical axis is multiplied by the ion's charge number squared (Z^2).

Essentially the result is that the ionizing power increases as the particle energy decreases, so as to cause the more slowly moving particles to be the most damaging. In the extreme relativistic energy region the damage effects are basically constant–at a level which is termed the ionization minimum. At the lowest velocities the charged particles are finally neutralized by picking up electrons.

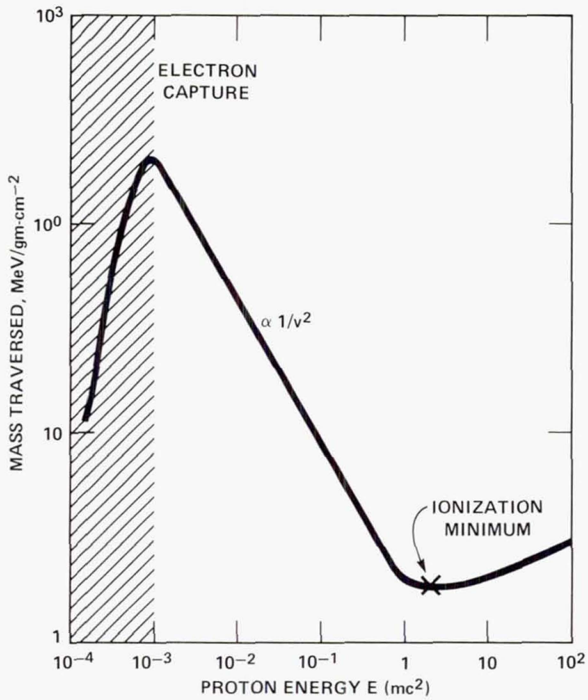

Figure 2-8.– *Ionizing power of protons in SiO_2 vs. energy.*

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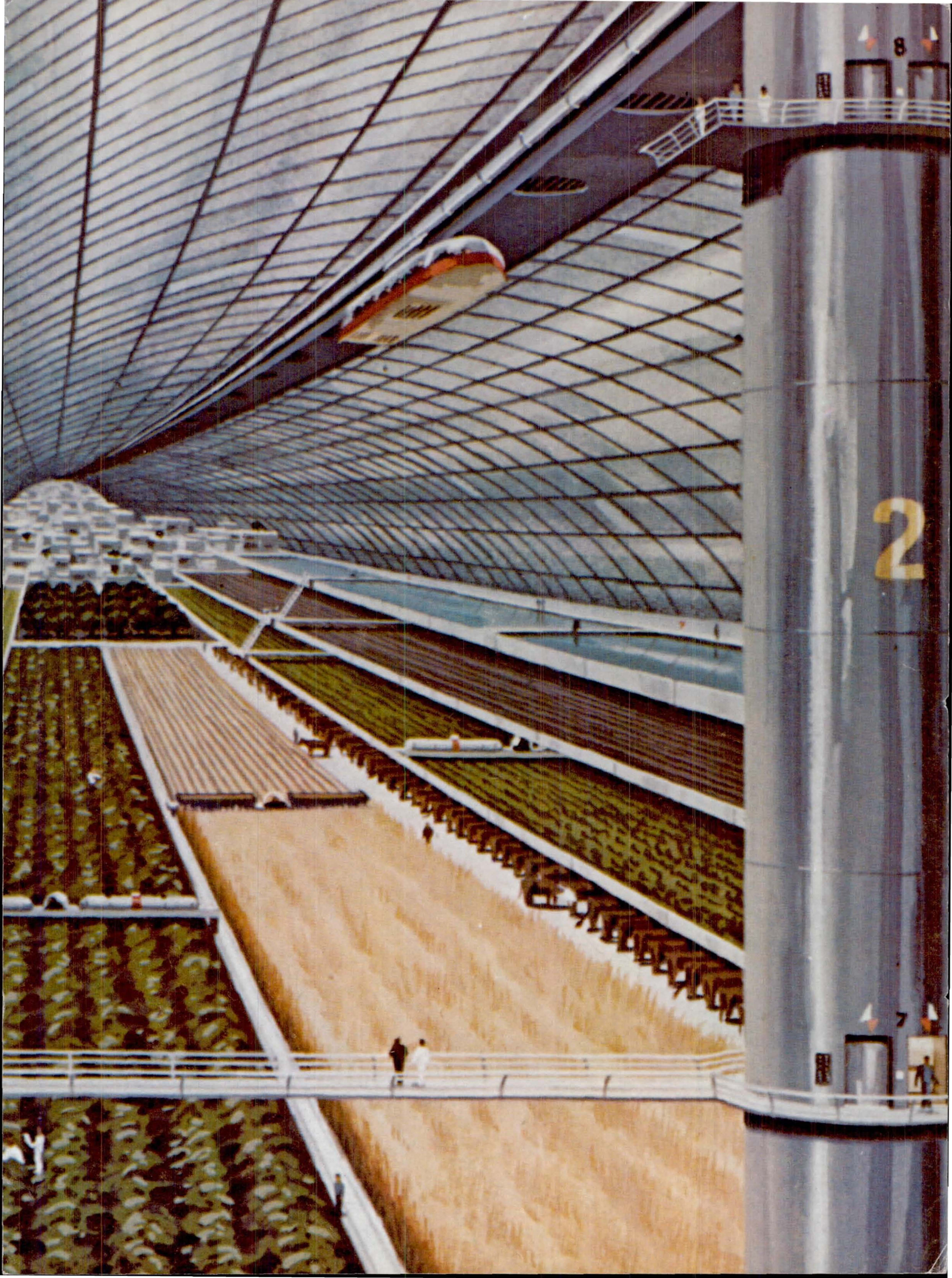

3. Human Needs in Space

Elementary essentials such as air, water, food, and even the sensation of weight all have to be provided to the space colony. Engineering criteria to assure physiological safety and comfort are essential, but equally important is to provide for psychological and esthetic needs of the colonists.

The structure, mass, and shape of the habitat are sensitive to the choice of design criteria. Rather substantial savings in structural mass, and hence in cost and construction time, can be obtained by deviating from Earth-like conditions. Because the physiological effects of appreciable deviations from some of the terrestrial conditions are unknown, the living conditions in space are designed to be similar to those on Earth despite additional costs. The treatment of weightlessness is an example of this conservative approach.

WEIGHTLESSNESS: PSEUDOGRAVITY IS NEEDED

An outstanding feature of space is the absence of the sensation of weight. In vessels moving freely in orbit objects exhibit weightlessness; they are said to be in "free fall," or subject to "zero gravity" or "zero g." Weightlessness is a major potential resource of space, for it means humans can perform tasks impossible on Earth. Large masses do not require support, and their movement is restricted only by inertia. Structures can be designed without provision for support against the forces of gravity; in free space there is no such thing as a static load. Although these opportunities are only beginning to be explored, it seems likely that weightlessness will permit novel industrial processes (refs. 1,2). Moreover, in free space, levels of pseudogravity can be produced and controlled over a wide range of values. This capability should foster the development of manufacturing processes not possible on Earth. Despite these potentially important commercial advantages of life in free fall, possible physiological consequences are of concern.

On Earth, gravity subjects everyone continuously and uniformly to the sensation of weight. Evolution occurred in its presence and all physiology is attuned to it. What happens to human physiology in the absence of gravity is not well understood, but experience with zero g is not reassuring. In all space flights decalcification occurred at a rate of 1 to 2 percent per month (ref. 3), resulting in decreased bone mass and density (ref. 4). There is no evidence to suggest that the rate of calcium resorption diminishes even in the longest Skylab mission of 89 days (ref. 5). Longer exposures could lead to osteoporosis and greatly reduced resistance to fracture of bones on minor impact. Moreover, because the body presumably draws calcium from the bones to correct electrolyte imbalances (ref. 4), it is clear that in zero g over many weeks and months a new equilibrium in the cellular fluid and electrolyte balance is not achieved. Furthermore, hormone imbalances also persist. In the later stages of some missions suppression of steroid and other hormone excretions were noted, together with reduction of norepinephrine output (ref. 3), unstable protein and carbohydrate states (ref. 5), indications of hypoglycemia, and unusual increases in secondary hormone levels with corresponding increases in primary hormones (private communication from J. V. Danellis, NASA/Ames Research Center).

The medical problems on returning to Earth from zero g are also significant. Readaptation to 1 g has been almost as troublesome as the initial changes due to weightlessness. Following even the relatively short missions that have been flown to date astronauts have experienced increases of 10-20 beats/min in heart rate, decreased cardiac silhouette, changes in muscle reflexes, venous pooling, and leucocytosis (refs. 3-5). Although changes in physiology have been reversible, it is not known whether this will be so after prolonged weightlessness. Vascular changes, such as reduction in the effectiveness of veins or variations in the pattern of response of mechano-receptors in the walls of blood vessels, or changes such as decrease in the effectiveness of the immune system, or the manifestation of differences in fetal development (especially possible inhibitions of the development of the balance mechanism of the inner ear), may become irreversible.

From present knowledge of the effects of weightlessness on physiology it seems appropriate to have at least some level of gravity acting on humans in space most of the time. Levels below the Earth normal (1 g) are not considered because there is no data on the effects of long-term exposure to levels of gravity between zero and one. Consequently because short term excursions into weightlessness reveal the complexity of the resulting physiological phenomena, and because the study group decided to be cautious in the absence of specific information, a criterion for safe permanent habitation is adapted – that the residents should live with the same sensation of weight that they would have on the Earth's surface, namely 1 g. Some variation about this figure is inevitable and so it is specified that humans permanently in space should live between 0.9 g and 1 g. This choice of a 10 percent variation is arbitrary, but also maintains conditions as Earth-like as possible.

The decision to provide 1 g to the colonists means they must reside in a rotating environment; the most feasible way to generate artificial gravity. However, in a rotating system there are forces acting other than the centrifugal force which supplies the pseudogravity. Thus, although the inhabitant at rest in the rotating system feels only the sensation of weight, when he or she moves, another force, called the "Coriolis force," is felt. The Coriolis force depends upon both the speed of motion and its direction relative to the axis of rotation. The direction of the force is perpendicular to both the velocity and the axis of rotation. Thus if the person in figure 3-1 jumps off the mid-deck level of the rotating torus to a height of 0.55 m (21.5 in.), because of Coriolis force he would not come straight down, but would land about 5.3 cm (more than 2 in.) to one side. At low velocities or low rotation rates the effects of the Coriolis force are negligible, as on Earth, but in a habitat rotating at several rpm, there can be disconcerting effects. Simple movements become complex and the eyes play tricks: turning the head can make stationary objects appear to gyrate and continue to move once the head has stopped turning (ref. 6).

This is because Coriolis forces not only influence locomotion but also create cross-coupled angular accelerations in the semicircular canals of the ear when the head is turned out of the plane of rotation. Consequently motion sickness can result even at low rotation rates although people can eventually adapt to rates below 3 rpm after prolonged exposure (ref. 6).

Again a design parameter must be set in the absence of experimental data on human tolerance of rotation rates. Although there has been considerable investigation (refs. 7-20) of the effects of rotating systems on humans the data gathered on Earth do not seem relevant to living in space. Earth-based experiments are not a good approximation of rotation effects in space because most tests conducted on Earth orient the long axis of the body parallel to the axis of rotation. In space these axes would be mutually perpendicular. Also on Earth a spinning laboratory subject still has Earth-normal gravity acting as a constant reference for the mechanism of the inner ear.

Although most people can adapt to rotation rates of about 3 rpm, there is reason to believe that such adaptation will be inhibited by frequent, repeated changes of the rate of rotation. This point is important because colonists living in a rotating system may also have to work in a non-rotating environment at zero g to exploit the potential benefits of weightlessness. For a large general population, many of whom must commute between zero g and a rotating environment, it seems desirable to minimize the rotation rate. There is a lack of consensus in the literature and among experts who have studied the problem on the appropriate upper limit for the rotation rate (refs. 21-28). For the conditions of the space colony a general consensus is that not more than several rpm is acceptable, and for general population rates significantly greater than 1 rpm should be avoided. Therefore, 1 rpm is set as the upper limit of permissible rotation rate for the principal living quarters of the colonists, again reflecting the conservative design criteria.

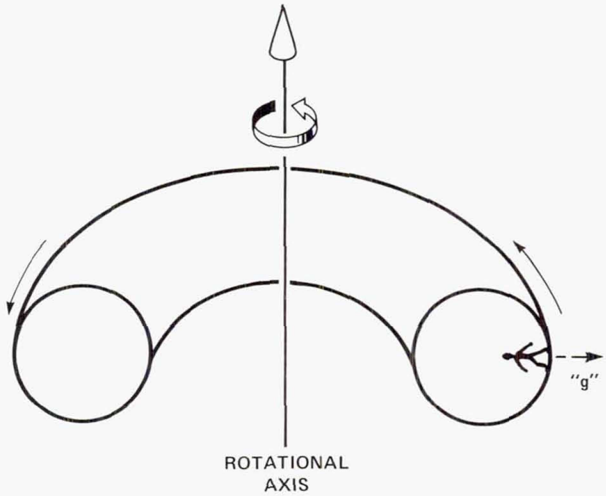

Figure 3-1.– *A rotating system (used to illustrate Coriolis force).*

ATMOSPHERE: LESS IS ENOUGH

To maintain life processes adequately the human organism requires an atmosphere of acceptable composition and pressure. The atmosphere of the space habitat must contain a partial pressure of oxygen (pO_2) sufficient to provide high enough partial pressure within the alveoli of the lungs (~13.4 kPa or ~100 mm Hg) for good respiration yet low enough to avert losses in blood cell mass and large changes in the number and distribution of micro-organisms, such as the growth of "opportunistic" bacteria (refs. 4,29). The value of pO_2 at sea level on Earth is 22.7 kPa (170 mm Hg) which sustains the needed oxygen in the blood. The range of tolerable variation is large and not well defined, but for general populations deviations of more than 9 kPa (70 mm Hg) in either direction seem unwise (ref. 30).

The presence of an inert gas in the colony's atmosphere is desirable since it would prevent an unusual form of decompression from occurring in the body's chambers and sinuses, while providing a greater safety margin during either accidental pressure drops or oxygen dilution by inert gases (ref. 31). Although several other gases have been used for this purpose, there are several reasons why nitrogen appears the most reasonable candidate for the colony. For example, since nitrogen constitutes almost 80 percent of the Earth's atmosphere, it is not surprising to find that some organisms require the gas for normal development (ref. 31). Further, with time, denitrifying bacteria will release nitrogen gas into the atmosphere, thereby resulting in the eventual accumulation of significant quantities. Finally, the inclusion of nitrogen-fixing plants in the colony's life support system means that the gas level can be biologically maintained by the conversion of nitrogen gas into protein. Thus the inevitable presence and the various benefits of nitrogen gas dictate its inclusion in the atmosphere, perhaps at a level of 26.7 kPa (~200 mm Hg).

The level of carbon dioxide should be maintained below the OSHA standard (ref. 32), which specifies that pCO_2 be less than 0.4 kPa (3 mm Hg). At the same time the CO_2 levels will be high enough to permit maximum rates of photosynthesis by crop plants. Trace contaminants should be monitored and controlled to very low levels.

Finally, it is desirable to maintain a comfortable relative humidity and temperature. Various sources (ref. 30) suggest a range of temperatures around 22° C and a relative humidity of about 40 percent. This criterion implies a partial pressure of water vapor (pH_2O) of 1.0±0.33 kPa (7.5 ± 2.5 mm Hg).

A major consequence of these various criteria is that human life can be safely and comfortably supported at a pressure well below that of a normal Earth atmosphere (ref. 31). The grounds for choosing a particular value are discussed in chapter 4.

FOOD AND WATER

Humans living in space must have an adequate diet; and food must be nutritious, sufficiently abundant, and attractive. There must be enough water to sustain life and to maintain sanitation. A diet adequate for a reasonable environmental stress and a heavy workload requires about 3000 Cal/day. It should consist of 2000 g of water, 470 g dry weight of various carbohydrates and fats, 60 to 70 g dry weight of proteins, and adequate quantities of various minerals and vitamins.[1] The importance of the psychological aspects of food should not be neglected. The variety and types of food should reflect the cultural background and preferences of the colonists.

COMBINED ENVIRONMENTAL STRESSES: PROBABLY NOT SERIOUS

While very little is known about physiological response to individual environmental stresses, even less is known about combined effects. The long-term, cumulative, interactive effects of biodynamic factors (hypogravity, Coriolis forces), atmospheric factors (composition, pressure, temperature), radiation and electromagnetic factors (illumination quality and periodicity, magnetic field strength), temporo-spatial factors, and other environmental factors could be additive ($E_{total} = \sum_{i=1}^{n} E_i$), synergistic ($E_{total} > \sum_{i=1}^{n} E_i$), or antagonistic ($E_{total} < \sum_{i=1}^{n} E_i$) (ref. 33).

It seems probable that if a substantial effort is made to provide reinforcing stimuli for maintaining biological rhythm (solar spectral and intensity distribution) (ref. 34) and diurnal periodicity (ref. 35), adequate nutrition, and a pleasant living environment, the problems of combined environmental stress would prove minimal.

ENVIRONMENTAL DESIGN TO REDUCE STRESS

To satisfy the physical needs of people in a way consistent with the goals described in chapter 1, habitable environments have to be created with maximum efficiency and minimum mass. Unless design criteria are carefully set, such environments may be so artificial or so

[1] Sweet, Haven, Florida Technological University, Orlando, Fla., personal communication, July 1976.

crowded as to exert damaging psychological stresses on the inhabitants. The psychological needs are discussed more fully in appendix A. Moreover, the extreme novelty of the surroundings or the sense of isolation of living in space may be stressful. It is the task of the architectural (ref. 36) and environmental designer to reduce such stresses by shaping and interrelating structures and surroundings to meet the psychological, social, cultural and esthetic needs of the colony's inhabitants while also satisfying their vital physiological needs.

Diversity and Variability

Environmental psychologists and behavioral scientists (refs. 37-39) have pointed out that variety, diversity, flexibility and motivation can make apparently deficient environments quite satisfactory to their inhabitants. It is important that space colonists become meaningfully involved in their environment. This can result from there being a planned complexity and ambiguity (ref. 38), that is, the design of the habitat must not be so complete as to be sterile; it must avoid motel banality. The ideal is to build a setting that provides individuals and groups alternate ways of satisfying their goals, thus giving them freedom of choice. Attaining such an ideal is greatly facilitated by the large size of the habitat which frees from limitations planned for in the small interiors of space stations.

In particular the interior should have a general plan so that the finishing and details can be left to the choice of the colonists themselves. Emphasis in the design of living area of a space colony should not be on specifics, but on the range of options. Colonists need access to both large and small, private and community spaces, to long vistas and short ones, but with a flexible, manipulatable architecture. They need to be able to exploit and to change these spaces according to individual wants. The initial design must permit the colonists to reshape the interior by developing and altering the spaces.

To these ends a building system must be developed which is fairly flexible, light weight, easily mass produced, capable of fast efficient erection, and yet allows a variety of spaces to evolve. It must also provide a sufficient esthetic quality, both materially and spatially. These criteria suggest a system that is built from modular components; that is, panels and structural elements that are uniform in size but when stacked or laid horizontally allow any combinations of shapes to be achieved.

There are ways to offset the undesirable effects of artificiality other than by facilitating individual variation. One is to provide large-scale vistas, that is, to make the habitat large enough to lessen the sense of its being man-made. To this end it may be desirable to limit a colonist's view so that the entire structure cannot be seen in a single scan by designing it so that some parts are always out of sight of others. Natural objects might also be simulated, but such simulation is usually recognized as being false. It then exaggerates the sense of artificiality, although it is possible to represent the natural environment by miniature design with a high degree of perfection and satisfaction, as in Japanese gardens. A better idea is to provide contact with the actual environment of space. Convenient access to regions of zero gravity and to views of the Earth, the Moon, and stars would provide stimuli taking full advantage of life in space; it also would provide panoramic vistas, long lines of sight, and awareness of reality beyond the human scale.

On a smaller scale the artificiality of the interior would be reduced by the presence of live, growing things such as vegetation for eating or for decoration, children playing and exhibiting the chaos of youth, or animals such as pets or livestock. Living things should be provided as an integral part of the interior architecture of the colony. The desire here is to have an environment that is not completely regimented. To that end, it might be desirable to have some random variation in the climate, but the politics of producing fluctuations in temperature and humidity are probably best left to the colonists themselves.

Space Needs Within the Colony

To design a human habitation in space, a criterion must be set for area available, most conveniently expressed in terms of area per person. The amount of area allocated per person has two important consequences: it determines the population density of habitation on which depends the sense of crowding; it limits services and facilities provided to the inhabitants.

A brief survey of the literature (refs. 40-43) indicates that there should be at least 40 m^2 of projected area per inhabitant. Projected area means area projected onto the largest plane perpendicular to the direction of the pseudogravity. Thus a three-story house with 60 m^2 of floor space occupies only 20 m^2 of projected area. Actual usable area can be made larger than projected area by constructing levels within a habitat, or several stories within a building. As table 3-1 shows, 40 m^2 per person is rather less than the area per person in most U.S. cities, although it is more than in some small French villages. It is an important task of space colony architects to organize this space to minimize the sense of crowding, while still providing needed services.

TABLE 3-1.– AVAILABLE LAND PER CAPITA IN SELECTED CITIES AND TOWNS

Location	Per capita area, m^2/person
Boston, Mass.	185.8
Chicago, Ill.	171.2
El Paso, Tex.	950.5
Jersey City, N.J.	150.1
New York, N.Y.	98.3
Manhattan Borough, N.Y.	38.2
San Francisco, Calif.	164.3
St. Paul, France	27
Vence, France	46.2
Rome, Italy	40.0
Columbia, Md.	503
Soleri's Babel IIB	15.1
Space colony	$\geqslant$40.0

Based upon experience with Earth cities, the needs of a community of 10,000 for living area and volume are categorized and a land-use plan is developed together with quantitative estimates of the volumes and areas needed. Some of the major spaces that must be provided are:

1. Residential – dwelling units, private exterior space, pedestrian access space
2. Commercial business – shops, offices
3. Public and semipublic enclosed space – government offices, hospitals, schools (with community multimedia center), churches (which may also serve as community and assembly halls), recreation, and entertainment
4. Public open space – parks, outdoor recreation (swimming, golf, playgrounds), zoo
5. Light service industry – personal goods, furniture, handicrafts, etc.
6. Wholesaling and storage
7. Space for mechanical subsystems – electrical distribution and transformer substations, communication and telephone distribution, air movement and distribution, water treatment (supply, return, recycling), sewage treatment
8. Transportation
9. Agriculture

To estimate the area and volume required for these various purposes, it is helpful to consider the organization and distribution of space within cities on Earth. Environmental psychologists and planners have long realized that sufficient area must be provided so that an individual can escape at least temporarily from the pressure of crowds. Parks and open spaces near high density neighborhoods are as important in space as on Earth (ref. 43). Space offers some possibilities for reducing apparent population density that are not easily available on Earth, such as by stacking areas in widely spaced levels or having within the same habitat different communities working and sleeping on different schedules so that their inhabitants could use the same recreational area but at different times (ref. 44). Less unusual would be to use certain areas for more than one purpose; for example, churches could also serve as assembly halls, and orchards could double as parks. In appendix B a detailed examination is made of areas and volumes required for these various functions, assuming some multipurpose usage. The results of this study are summarized in table 3-2. They suggest that, to meet community needs, 47 m^2 of projected area and 823 m^3 of volume are needed for each inhabitant. Agriculture requires an additional 20 m^2/person and 915 m^3/person. The justification of these last two numbers depends on how the design criterion of providing sufficient quantities of nutritious food is met; a topic discussed further in the next two chapters.

SMALL SIZE AND ISOLATION

The vastness of space and the smallness of the colony strongly affect the social, physical and governmental organization of the colony. Like any other human community, the colony has to specialize in exploitation of peculiar features of its environment to optimize its productivity. The fruits of this exploitation must be exchanged for the products of other specialized communities; trade with Earth is essential. The importance of trade is magnified by the small size of the colony which forces it to depend on Earth for many services and goods which are essential to modern society but often taken for granted. Furthermore, given that travel times among the components of the colony and to Earth may be of several days and also very expensive, it is clear that the transportation system is exceedingly important and that unusual emphasis must be placed on electronic communications and on trade in intangible goods and services.

Trade is Essential

It has been empirically demonstrated that self-sufficiency grows with size in modern high-energy societies. For communities of 10,000 people there is

TABLE 3-2.– SUMMARY OF COMMUNITY SPACE AND AREA ALLOCATIONS

Space use	Surface area required, m^2/person	No. of levels	Projected area, m^2/person	Estimated height, m	Volume, m^3
Residential	49	4	12	3	147
Business					
Shops	2.3	2	1.0	4	9.2
Offices	1	3	.33	4	4.0
Public and semipublic					
Schools	1	3	.3	3.8	3.8
Hospital	.3	1	.3	5	1.5
Assembly (churches, community halls)	1.5	1	1.5	10	15
Recreation and entertainment	1	1	1	3	3
Public open space	10	1	10	50	500
Service industry	4	2	2	6	24
Storage	5	4	1	3.2	16
Transportation	12	1	12	6	72
Mech. subsystem					
Communication distr. switching equipment for 2800 families	.05	1	.05	4	.2
Waste and water treatment and recycling	4	1	4	4	16
Electrical supply and distribution	.1	1	.1	4	.4
Miscellaneous	2.9	3	1	3.8	11.2
Subtotals	94.2		46.6		823.3
Agriculture space requirements[a]					
Plant growing areas	44	3	14.7	15	660
Animal areas	5	3	1.7	15	75
Food processing, collection, storage, etc.	4	3	1.3	15	60
Agriculture drying area	8	3	2.7	15	120
Totals	155.2		67.0		1738.3

[a]Agricultural space requirements are provided for completeness and convenience. The details are explained in the succeeding chapters.

NOTE: The areas and volumes arrived at are approximations for use in establishing mass estimates and aiding in the structural design of the entire habitat enclosure.

little hope of achieving self-sufficiency as measured by lack or absence of trade. There have been studies of sociology, economics, and geography which indicate the degree to which various specialities can be sustained. Colin Clark, one of the world's distinguished students of economic organizations, reports (ref. 45) that cities need populations of 100,000 to 200,000 in order to provide "an adequate range of commercial services. . . ." Moreover, populations of 200,000 to 500,000 are required to support broadly-based manufacturing activity.

A small settlement in space, of less than 100,000 people, would necessarily require continuing support from Earth. There is little possibility that such a settlement can be sustained without a steady and sizable movement of materials and information between Earth and the colony. Because of high demands on material productivity, ordinary business services such as banking, insurance, bookkeeping, inventory control, and purchasing would very likely remain on Earth. Management of the transportation system, and sales and delivery of products would be Earth based. The highly technological and specialized services of medicine, higher education and even of those branches of science and engineering not used in the day-to-day life of the colony would come from Earth. A community of 10,000 cannot conceivably support a large research university or a large medical center. Communities of this size on Earth do not encompass much social and cultural variety, and their major productive activities are usually limited in kind and number. To point up the lack of diversity that may reasonably be expected, consider how many and what variety of religious organizations and sects might be expected in a space colony of size 10,000.

Economies of scale for communities suggest an optimal size well above that of the early settlement in space.

Isolation: Offset by Transportation and Communications

While the small size of the colony exaggerates its dependence on Earth, the vastness of space and the long times and expense of travel tend to isolate the colonists from the home planet. A good design must attempt to anticipate and offset the effects of such isolation.

Travel from the colony to Earth is expensive, and takes a number of days. Given the need for trade and for the importation of many items of high technology that a small community cannot supply itself, the transportation system is exceedingly important. It seems essential to provide for "return migration" of persons and families to Earth who strongly wish for it, although it might be necessary to devise ways to discourage commuting.

The difficulty of physically transporting goods or people leads to a strong emphasis on electronic communication. Direct lines of sight from the colony to the Earth make radio, television, and facsimile transmission easy. Many of the special services mentioned earlier could be supplied remotely, for example, accounting, education, and even many medical diagnostic services can be performed electronically. Consequently a colony in space is expected to have highly developed electronic communications for commerce, education, entertainment and community activities. These should be designed to be easily accessible to the members of the colony, probably with two-way capability and linked to computers. The network is of such importance that it should have a high degree of redundancy for reliability, and be designed to assure privacy. It is likely that both the physical and social organization of the community will be shaped around the communications system.

Governance and Social Order

Distance and isolation also affect the governance and social order. Whether space colonization is a unilateral effort on the part of the United States or a cross-national enterprise, it will most likely be sponsored by a public or quasipublic organization with a bureaucratic structure which permeates the early settlement. The sense of isolation may stimulate the organizational development of communities away from the organizational form of the sponsor as the interests and life circumstances of a rapidly growing population change and develop. The form of governance depends very much on the preferences of the settlers, in much the same way as allowances for individual choice have been emphasized in other considerations of life in space.

Maintenance of order and of internal as well as external security initially falls to the Earth-based sponsoring organizations and then to the organized community which is expected to rise early in the colony's history. The small size of the settlement, combined with a rather precarious manufactured environment, may emphasize a concern for internal security. Any individual or small group could, in prospect, undertake to destroy the entire colony by opening the habitat to surrounding space, by disrupting the power supply, or by other actions which have few corresponding forms in Earth-based settings. Whatever organizational form the colonists evolve, it must be able to assure the physical security of the habitat and its supporting systems, and this need for security may infringe upon other desirable features of the colony and its operation.

SUMMARY OF DESIGN CRITERIA

The following physiological, environmental design, and organizational criteria must be met by a successful space habitat for the colonization of space.

Physiological Criteria

The basic physiological criteria are summarized in table 3-3.

TABLE 3-3.– A SUMMARY OF PHYSIOLOGICAL CRITERIA

Pseudogravity	0.95 ± 0.5 g
Rotation rate	$\leqslant 1$ rpm
Radiation exposure for the general population	$\leqslant 0.5$ rem/yr
Magnetic field intensity	$\leqslant 100\ \mu T$
Temperature	$23° \pm 8°$ C
Atmospheric composition	
pO_2	22.7 ± 9 kPa (170 ± 70 mm Hg)
p(Inert gas; most likely N_2)	$26.7\ kPa < pN_2 < 78.9\ kPa$ ($200 < pN_2 < 590$ mm Hg)
pCO_2	<0.4 kPa (<3 mm Hg)
pH_2O	1.00 ± 0.33 kPa (7.5 ± 2.5 mm Hg)

Environmental Design Criteria

The criteria for environmental design are both quantitative and qualitative. Quantitative criteria are summarized in table 3-4. Desirable qualitative criteria are summarized in table 3-5.

TABLE 3-4.– SUMMARY OF QUANTITATIVE ENVIRONMENTAL DESIGN CRITERIA

Population: men, women, children	10,000
Community and residential, projected area per person, m^2	47
Agriculture, projected area per person, m^2	20
Community and residential, volume per person, m^3	823
Agriculture, volume per person, m^3	915

TABLE 3-5.– SUMMARY OF QUALITATIVE CRITERIA OF ENVIRONMENTAL DESIGN

Long lines of sight
Large overhead clearance
Noncontrollable unpredictable parts of the environment; for example, plants, animals, children, weather
External views of large natural objects
Parts of interior out of sight of others
Natural light
Contact with the external environment
Availability of privacy
Good internal communications
Capability of physically isolating segments of the habitat from each other
Modular construction
of the habitat
of the structures within the habitat
Flexible internal organization
Details of interior design left to inhabitants

Organizational Criteria

The organizational criteria have to do with both physical organization and social and managerial organization. In the first category is the criterion that the components of the colony be located so that the resources of space can be effectively exploited: solar energy, matter in the Moon or asteroids and on Earth, high vacuum of space and possibilities of pseudogravity variable from 0 g to more than 1 g. The colony must be provided with a transportation system that is capable of sustaining close contact with Earth, and with extensive electronic communications.

The organization of the governance of the colony is less restrained by specific criteria than are other aspects of life in space. Nevertheless, the organization must be such as to permit comfortable life under crowded conditions far from other human communities. Moreover, the organization must facilitate a high degree of productivity, foster a desirable degree of diversity and heterogeneity, and maintain the physical security of the habitat.

The next chapter considers a number of alternative ways of meeting these criteria. From the various alternatives the particular design is then selected and justified.

APPENDIX A

PSYCHOLOGICAL AND CULTURAL CONSIDERATIONS

Several geometrical forms for the physical shape of space communities have been studied: including a cylinder of a few kilometers in diameter; a torus of a few kilometers in diameter and several tens of meters in cross section; a bundle of narrower parallel toruses; a necklace shape consisting of small spheres; a pair of large spheres, each of which has a diameter of several kilometers. They were examined from the points of view of volume, mass, rotational speed, shielding needed, construction and costs, as described in the next chapter. However, there are also some psychological considerations of physical shape which affect the mental health of the inhabitants. Different geometrical forms of the communities may also influence the types of social interactions and social organization which take place in them.

The Solipsism Syndrome in Artificial Environment

Some environments are conducive to the state of mind in which a person feels that everything is a dream and is not real. This state of mind occurs, for example, in the Arctic winter when it is night 24 hr a day. It is also known to occur in some youths who have been brought up on television as a substitute to reality.

Solipsism is a philosophical theory that everything is in the imagination, and there is no reality outside one's own brain. As a philosophical theory it is interesting because is is internally consistent and, therefore, cannot be disproved. But as a psychological state, it is highly uncomfortable. The whole of life becomes a long dream from which an individual can never wake up. Each person is trapped in a nightmare. Even friends are not real, they are a part of the dream. A person feels very lonely and detached, and eventually becomes apathetic and indifferent.

In the small town of Lund, Sweden, the winter days have 6 hr of daylight and 18 hr of darkness. Most of the time people live under artificial light, so that life acquires a special quality. Outdoors, there is no landscape to see; only street corners lit by lamps. These street corners look like theater stages, detached from one another. There is no connectedness or depth in the universe and it acquires a very unreal quality as though the whole world is imagination. Ingmar Bergman's film "Wild Strawberries" expresses this feeling very well.

This state of mind can be easily produced in an environment where everything is artificial, where everything is like a theater stage, where every wish can be fulfilled by a push-button, and where there is nothing beyond the theater stage and beyond an individual's control.

There are several means to alleviate the tendency toward the solipsism syndrome in the extraterrestrial communities:

1. A large geometry, in which people can see far beyond the "theater stage" of the vicinity to a view which is overwhelmingly visible.

2. Something must exist beyond each human's manipulation because people learn to cope with reality when reality is different from their imagination. If the reality is the same as the imagination, there is no escape from falling into solipsism. In extraterrestrial communities, everything can be virtually controlled. In fact, technically nothing should go beyond human control even though this is psychologically bad. However, some amount of "unpredictability" can be built in within a controllable range. One way to achieve this is to generate artificial unpredictability by means of a table of random numbers. Another way is to allow animals and plants a degree of freedom and independence from human planning. Both types of unpredictability must have a high visibility to be effective. This high visibility is easier to achieve in a macrogeometry which allows longer lines of sight.

3. Something must exist which *grows*. Interactive processes generate new patterns which cannot be inferred from the information contained in the old state. This is not due to randomness but rather to different amplification by mutual causal loops. It is important for each person to feel able to contribute personally to something which grows, that the reality often goes in a direction different from expectation, and finally that what each person takes care of (a child, for example) may possess increased wisdom, and may grow into something beyond the individual in control. From this point of view, it is important personally to raise children, and to grow vegetables and trees with personal care, not by mechanical means. It is also desirable to see plants and animals grow, which is facilitated by a long line of sight.

4. It is important to have "something beyond the horizon" which gives the feeling that the world is larger than what is seen.

Types of Social Organization

There are many different types of social organization based on different cultural philosophies. The following exaggerated examples are discussed to suggest how each may be facilitated or made difficult by various forms of macrogeometry of a space colony.

Type A Community: Hierarchial and Homogenistic

People in this community believe that if there are many ways, there must be the best way among them, and that the "best way" is "good" for everybody. They think in terms of maximization and optimization. They consider majority rule as the basis of democracy, and competition as the basis of "progress." They look for universal criteria and universal categories which would apply to all people, and they look for unity by means of similarities. Differences are considered as accidental, inconvenient or bothersome, and are ignored as much as possible. Diversity, nonstandard behavior, and minority groups are considered abnormal and undesirable, to be corrected to be more "normal." If these people are inconvenienced by the system which is geared toward the majority, the fault is considered to reside in the "abnormal" people. Because of the belief in the "best way" for all people and in maximum efficiency, all living units are designed alike. Because of the belief that unity is achieved by homogeneity and that differences create conflicts, residents are divided into age groups, occupational groups, and the like in such a way that each group is homogeneous within itself. Similarly, all living units are concentrated in one zone; recreation facilities in another zone; industrial facilites in the third zone. This allows for a large continuous area suitable for recreation activities which require large space.

Type B Community: Individualistic and Isolationistic

People in this community think that independence is a virtue, both from the point of view of the person who is independent and from the point of view of others from whom he is independent. They consider self-sufficiency as the highest form of existence. Dependency and interdependence are looked down upon as weakness or sin. Each living unit is like a self-contained castle and is insulated against others in terms of sight, sound and smell. Each unit contains its recreational facilities, and there is no communal recreation area. Within each unit, everything is adjustable to the individual taste. Protection of privacy is a major concern in this type of community.

Type C Community: Heterogenistic, Mutualistic and Symbiotic

People in this community believe in the symbiosis of biological and social process due to mutual interaction. Heterogeneity is considered as a source of enrichment, symbiosis, resource diversification, flexibility, survival and evolution. They believe that there is no "best way" for all people. They think in terms of choosing and matching instead of maximization or optimization. They consider majority rule as homogenistic domination by quantity, and instead, use the principle of elimination of or compensation for hardship which even a single individual may suffer from when a decision – no matter which direction – is taken. They consider competition useless and cooperation useful. They think that criteria and categories should be flexible and variable depending on the context and the situation. They look for harmony and symbiosis thanks to diversity, instead of advocating unity by means of similarities. Homogeneity is considered as the source of quantitative competition and conflict. Houses are all different, based on different design principles taken from different cultures and from different systems of family structure, including communes. Each building is different, and within each building, each apartment is different. The overall design principle is harmony of diversity and avoidance of repetition, as is found in Japanese gardens and flower arrangement. Different elements are not thrown together but carefully combined to produce harmony. People of different ages, different occupations, and different family compositions are mixed and interwoven, but care is taken to place together people who can help one another. For example, old people who love children are placed near families who need babysitters. On the other hand, antagonistic combinations are avoided. For example, noisy people are not placed near people who love a quiet environment.

There are two different methods of heterogenization: localization and interweaving. In localization, each of the heterogeneous elements separates itself and settles in one locality. Chinatown in San Francisco is an example. In localization, heterogeneity increases between different localities, but each locality becomes homogeneous. On the other hand, in interweaving, different elements are interwoven together. This system creates no great differences between localities, but within each locality there is a great diversity. In the interwoven system, accessibility to different elements increases. It becomes easier for the individual to heterogenize himself. For example, a white person may eat Chinese food on Monday, Italian food on Tuesday, learn Judo on Wednesday, or become a full-time Tibetan Monk. Both localization and interweaving may be incorporated in the design of extraterrestrial communities.

The Problem of Matching

Individuals vary in their taste, abilities, and optimal rate of communication. No culture is "healthy" or "unhealthy" for everybody. Each culture is healthy for those whose tastes, abilities and rate of communication match with it, and unhealthy for others. High-communication individuals suffer in a low-communication community, and low-communication individuals suffer in a high-communication community. The same holds true for the matching of individuals to jobs, or individuals to individuals.

Successful matching requires availability of variety, and availability of variety depends on the number of different types of communities as well as the degree of heterogeneity within a community.

There is also the problem of size vs. number. For example, many areas of the Midwest have a large number of small colleges, each with 1000 or 2000 students. They all have libraries with more or less the same basic books. In a way this large number of small colleges creates heterogeneity. But in another sense a small number of large universities can create more heterogeneity, especially in the variety of library books or in the variety of departmental subjects. The planning of extraterrestrial communities presents similar problems.

Self-Sufficiency of an Extraterrestrial Community

One of the most frequently asked questions regarding the idea of extraterrestrial communities is whether they can be self-sufficient. There are several different criteria for self-sufficiency:

1. Ability to survive and develop without any interaction with other communities.
2. If isolated, ability to survive at a reduced level.
3. Inability to survive without interaction with other communities, but financially self-sufficient in the sense that the "export" and the "import" balance out.
4. Ability to produce for export.

Turnover of Personnel

There are three kinds of people who go to work in remote terrestrial areas such as Alaska: those who like adventurous life or like to challenge harsh, inconvenient life and enjoy it; those who have a romantic but unrealistic notion of adventurous life, find themselves incapable of living there, and return as soon as the first contract period is over; those who go for money, even though they hate the life in the remote area.

The percentage of the second and the third categories is very large. The material conditions in extraterrestrial communities will be comfortable; more comfortable than living in Washington D.C. in summer or in Boston in winter. What would probably make life in an extraterrestrial community "harder" than life in Minnesota or California is isolation from the Earth and smallness of the environment. In these two aspects, an extraterrestrial community resembles Hawaii rather than Alaska.

High monetary incentive should not be used for space colonization recruiting because it attracts the wrong people. Furthermore, it would be unhealthy for the community as well as for the individuals concerned to make efforts to retain "misfits" in the extraterrestrial community. It would be healthier to return them to the Earth, even though this might seem more "expensive."

During the feudal period in Japan, political offenders were often sent away and confined in small islands. This form of punishment was called "shimanagashi." In many American prisons today, there are "isolation units" and "segregation units" where inmates whom the prison authorities consider as "troublemakers" are confined for a length of time.

To a smaller degree, the "mainlanders" who spend a few years on an isolated island, even though the island may have large cities and modern conveniences, feel a strange sense of isolation. They begin to feel left out and intellectually crippled, even though physically life may be very comfortable. People suffer from the shimanagashi syndrome unless they were born on the island or have lived there a long time. For many people, life in Alaska has more challenge and excitement than life on a remote island. Often daily life in Alaska seems to consist of emergencies, which test resourcefulness and ability to cooperate with other individuals.

Furthermore, Alaska is not only part of a continent but also has travel possibilities that are almost unlimited in winter as a result of snow on land and ice on the ocean, both of which serve limitless highways for sleds and skis. On an island, however, one cannot go beyond the shoreline, whereas in Alaska one can travel far beyond the visible horizon.

Would the immigrants of extraterrestrial communities suffer from the shimanagashi syndrome? Journals and books can be transmitted electronically between the Earth and extraterrestrial communities, so that these communities are not isolated in terms of communication. However, in terms of physical travel they are isolated – at least between the Earth and extraterrestrial communities – because the Earth is at the bottom of a deep gravity well. But when numerous extraterrestrial communities have been constructed, travel between them will be quite inexpensive because the transportation system does not have to fight against the gravitational field.

International Participants

When there are many extraterrestrial communities, some may belong to different terrestrial nations, some may be international, and some may even form new extraterrestrial nations.

The first extraterrestrial communities may not be purely American if the United States is no longer a major world power or a major technological center by the time the first extraterrestrial community is established. If the United States remains a major world power, many nations including nonwestern nations and African nations, could be highly technological and want to participate, so that the first extraterrestrial community may be international.

The present technological nations are not necessarily advantaged, because the technology they possess is "Earth-bound" in addition to being culture-bound. They may have first to unlearn the forms, the assumptions and the habits of the Earth-bound technology before learning the new forms and assumptions of technology useful in extraterrestrial communities.

APPENDIX B

SPACE REQUIREMENTS OF VARIOUS COMMUNITY ACTIVITIES

To determine an appropriate allocation of space among the various community institutions such as schools, residences, factories, hospitals, etc., the study group used U.S. building standards and estimations of allocation of land use found in the extensive literature of community planning (ref. 46). Area and volume are apportioned to provide for a mature community in space with a population like that of a similar sized town on Earth.

The following paragraphs present much of the rationale for the allocations of area, projected area, and volume that are presented in table 3-2. Projected area and volume are simply derived from the total area allotted to a particular function. However, the projected areas in table 3-2 are obtained by dividing the total area by the number of levels in which the area is to be stacked, and the volume is obtained by multiplying the total area by the amount of overhead specified in that table.

Residences

Minimum room sizes for residences are determined from the Uniform Building Code for residential occupancies. An area of 148 m^2 for a family of four satisfies the requirements of the code comfortably. When space for external use and access is included, the following recommended minimums result: 37 m^2/person of floor area, 12 m^2/person of exterior space, totaling 49 m^2/person of total residential space. When 3 m is taken as a generous value for the overhead height in these spaces, the result implies a required minimum volume of 147 m^3.

To determine the projected area required per person it is necessary to divide the total area by the number of levels into which it is stacked. For the residential areas the stacking factor is taken to be 4, thus the required projected area is a little more than 12 m^2/person.

Shops and Offices

Area for shops is determined from recommendations of the Town Planning Committee of South Australia which calls for 10 shops per 1000 persons, each with a floor space of 1 m^2/person, an area for walkways and access of 1 m^2/person, and 0.3 m^2/person for expansion. The 2 m^2/person allotted to parking in these recommendations is, of course, not included for the space habitat.

In a similar way the same source is used to estimate an area of 1 m^2/person for office space.

Schools and Hospitals

Areas for schools are based upon an assumption that 6 percent of the habitat's children are in nursery school, 17.5 percent in elementary, 7.5 percent in junior high and 7.5 percent in high school. Adopting the highest value recommended, 10 m^2/person, and assuming 3-story schools, leads to 3.3 m^2/student. If student population is 10 percent of the total population, the required projected area is 0.3 m^2/person.

DeChiara and Koppelman (ref. 47) recommend a hospital capacity of 693 beds for 250,000 people. Scaled down to a community of 10,000 this is 28 beds. The calculation can also be done using the typical number of patients days per year for a population with the age distribution characteristic of the colony. The result is substantially the same: 26 beds. Because of the nature of the colony and its isolation, a more realistic number might be 50.

A 50-bed hospital including administrative, diagnostic, treatment, nursery, surgical, obstetrical, service, and circulation facilities requires 58 m^2/bed or 2900 m^2 total. The corresponding projected area is 0.3 m^2/person.

Assembly Halls

DeChiara and Koppelman specify 1.5 m^2/person for 10,000 people for general community facilities such as churches, community halls, and theaters. For recreation and entertainment, indoor activities, restaurants, and so on, the recommendation is 0.4 m^2/person. To include all commercial entertainment, 1 m^2/person is assumed.

Open Space

Averaged over 53 U.S. cities the open space for parks and such is 18 m^2/person. DeChiara and Koppelman recommend 14 m^2/person. Because the space habitat contains agricultural areas that can be in part used as open space, a lower value of open space in the residential area is adopted, namely 10 m^2/person. To allow a true feeling of being "open" the space has to be tall enough. This height is taken to be 50 m.

Light Industry

For the planning of new towns the Town Planning Committee of South Australia recommends 4 m^2/person for light service industries. An average over 53 U.S. cities gives 8 m^2/person. For planning purposes in the colony 4 m^2/person is assumed.

Storage

Storage space must be provided. Adelaide, Australia, in 1957 had approximately 7 m^2/person devoted to wholesaling and storage. The colony has 5 m^2/person alloted to these purposes.

Mechanical Subsystems

Provision must also be made for mechanical subsystems. By analogy with Earth-like situations, a total of 400 m^2 is allocated to communication distribution and switching equipment for 2800 families, 40,000 m^2 for waste and water treatment and recycling, and 1000 m^2 for electrical supply and distribution, a total of about 4.2 m^2/person. A major distribution tunnel is provided around the perimeter of the enclosure for mechanical facilities and services.

Transportation

About 24 percent of the total land use in U.S. metropolitan areas is devoted to transportation, that is, approximately 48 m^2/person (ref. 48). However, Earth-like streets are not needed in the compact, closely-knit organization of the colony. Where typical street right of way in U.S. urban communities averages a little over 18 m, 15 m seems adequate for the colony. Thus, only one fourth as much area need be allocated to transportation in the colony as on Earth. The numerical value is 12 m^2/person.

Because of the relatively high population density (15,000 people/km^2) in the community, most of the circulation is pedestrian, with one major mass transport system (a moving sidewalk, monorail, and minibus) connecting different residential areas in the same colony. Elevators could also be used to travel through the spokes to the far side of the colony. The diagram of figure 3-2 suggests approximate areas and volumes needed for different modes of transportation in the colony. The chosen mode would be in addition to major arteries, secondary paths, collector paths and local circulation paths within the community enclosure.

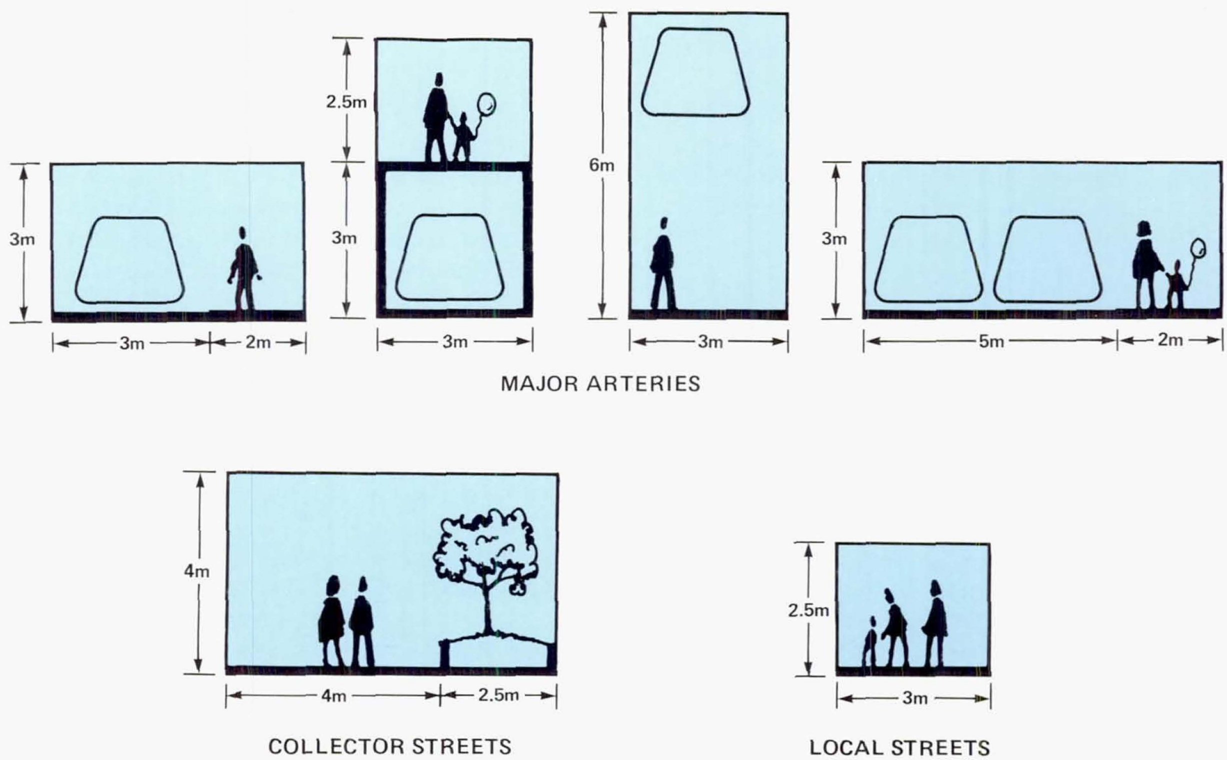

Figure 3-2.– *Alternative transportation modes in the colony.*

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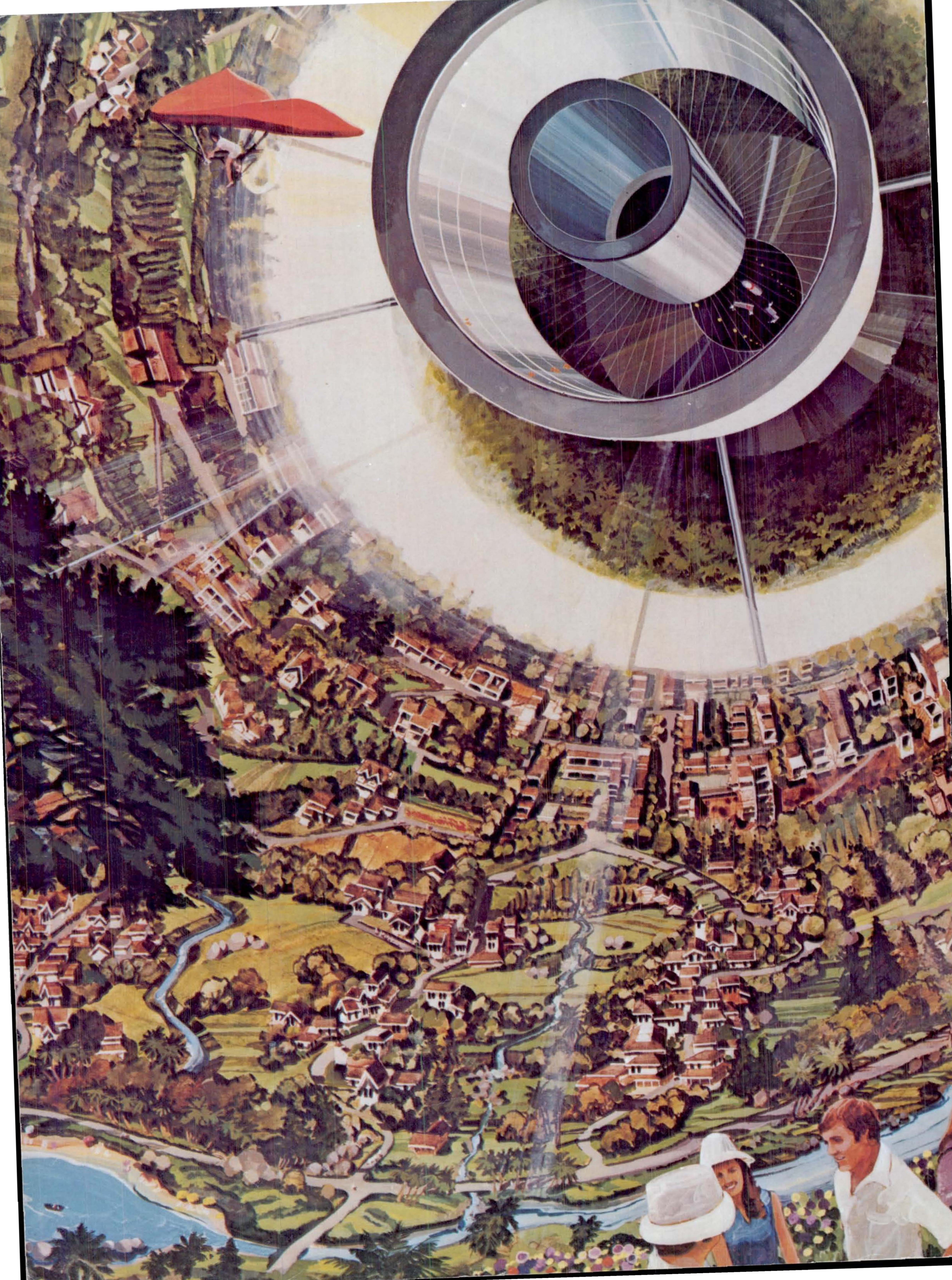

4. Choosing Among Alternatives

A few years after people move into the first colony, the system should settle down and operate as described in chapter 1. But why is the colony shaped as a torus and located at L_5 with ore supplies from the Moon? Why is it not a sphere out at the asteroids or near a moon of Mars, or a cylinder in geosynchronous orbit around the Earth, or some other combination of alternatives? What are these alternatives, and why were they rejected? The purpose of this chapter is to answer these questions by evaluating reasonable alternatives in terms of the goals of the design study (ch. 1) and the criteria laid out in chapters 2 and 3.

A successful systems design combines subsystems satisfying various conflicting criteria to produce a unified working entity. The parts of the space colony – transportation, mining, the habitat, manufacturing, agriculture, and so on – must interact and interrelate in such a way that the demands of each for energy, raw materials, manpower, transport, and waste removal can be met by the overall system. In turn this system must satisfy the physiological, cultural, architectural, and physical criteria necessary to maintain a permanent human community in space using near-term technology and at a minimum cost.

In 10 weeks the study group was able to assemble only one reasonably consistent picture of life in space; there was no time to go back through the system and attempt to find optimal combinations of the subsystems. Moreover, again because time was short, many of the comparisons among alternative subsystems were more qualitative than study group members would have liked.

Effort devoted to alternatives depended upon the particular subject. A great deal of time was spent considering different forms for the habitat, how to handle the shielding and how to process lunar material. Less time was given to considering alternative patterns of siting the colony and its parts, of different ways to achieve life support, or of various possible transportation systems. In some cases much effort was expended but few alternatives were generated; an example is the system for moving large amounts of matter cheaply from the Moon to the colony. No alternative at all was found to the manufacture of solar satellite power plants as the major commercial enterprise of the colony.

It is important to realize that the alternatives described in this chapter constitute a major resource for improving the proposed design and for constructing new designs that meet other criteria. Rejection of any concept for the current "baseline system" does not mean that concept is fundamentally flawed. Some alternatives were rejected because they failed to meet the criteria, which were deliberately chosen conservatively and might well be changed on the basis of future experience or under different assumptions. Others were rejected simply because information about them was incomplete. Yet others were not chosen because their virtues were recognized too late in the study to incorporate them into a unified overall picture.

The alternatives might also be useful for designing systems with other goals than permanent human settlement in space; for example, space factories with temporary crews, or laboratories in space. Alternatively, new knowledge or advances in technology, such as the advent of laser propulsion or active shielding against ionizing radiation, might make rejected subsystems very desirable.

THE SHAPE OF THE HABITAT

What shape is most suitable to house this colony of 10,000 people? The question is particularly interesting for several reasons. The appearance and arrangement of the habitat are most obvious and understandable by everyone, being the most direct exhibition of the reality of the idea of the colony – seeing the form is believing– and the habitat naturally attracts a great deal of attention although it is only one part of a much larger system. Moreover, the reader may already be aware of one or more possibilities: the rotating cylinders proposed by O'Neill (ref. 1), the torus of Von Braun (ref. 2), and their corresponding entities in the science fiction of Arthur C. Clarke (refs. 3,4). The subject is also one particularly suited for systematic treatment and can serve as an excellent example of the methodology of systems design.

Some General Considerations

Because it is expedient, although not entirely justified, to treat the shielding which protects against the dangerous radiations of space separately from the choice of the geometry of the habitat's structure, that problem is left to a subsequent section. Subject to possible effects of the shielding, the choice of habitat geometry is determined by meeting the criteria of the previous chapter at minimum cost. In considering how different configurations may supply enough living space (670,000 m^2) and how they meet the physiological and psychological needs of people in space, the following discussion uses the properties of materials outlined in appendix A. Throughout, aluminum is assumed as the principal structural material.

The Habitat Must Hold an Atmosphere

The simple fact that the habitat must contain an atmosphere greatly limits the possible forms. For economy in structural mass it is essential that large shells holding gas at some pressure must act as membranes in pure tension. There is, in turn, a direct relationship between the internal loading and the shape of the surface curve of such a membrane configuration. Also, when the major internal loads are pressure and spin-induced pseudogravity along the major radius of rotation, R, the possible membrane shapes must be doubly symmetric, closed shells of revolution (refs. 5,6). The

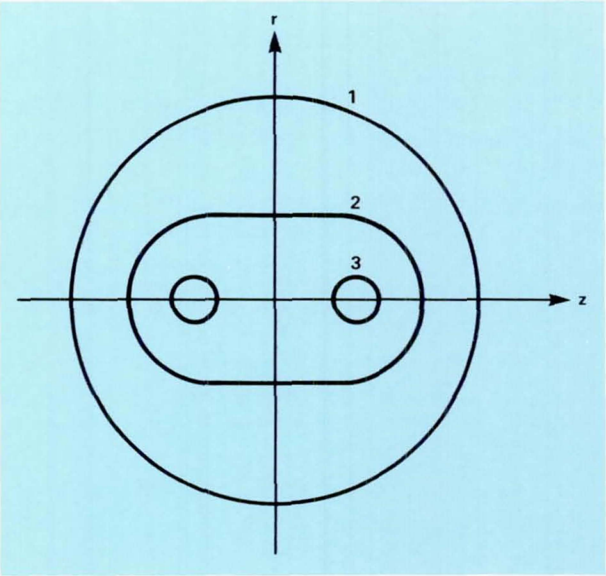

Figure 4-1.– *Subset of Cassini curves which, when revolved, generate possible geometrics.*

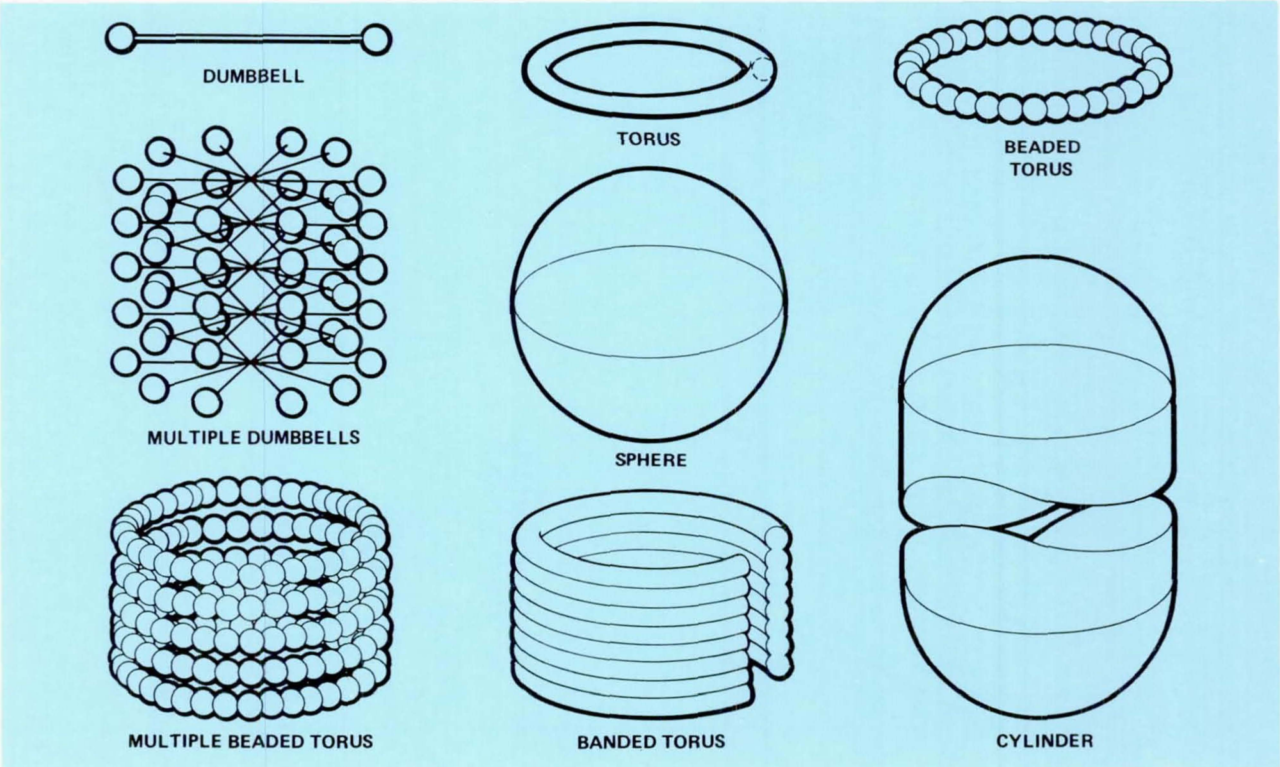

Figure 4-2.– *Basic and composite shapes.*

possible "smooth" shapes are the ones generated from the curves in figure 4-1. Four fundamental configurations arise:

1. A sphere – by rotating curve 1 about either axis
2. A cylinder – by rotating curve 2 about the z axis
3. A torus – by rotating curve 3 about the r axis
4. A dumbbell – by rotating curve 3 about the z axis

Neglecting secondary effects from variations in pseudogravity and localized bending stresses from discontinuities in deformations, the study group concluded that all possible membrane shapes, that is, any possible habitat, must be one of the four simple forms described above or some composite of them as shown in figure 4-2.

The desire to keep structural mass small favors small radii of curvature. As figure 4-3 shows, the wall thickness to contain a given pressure drops quickly with decreasing R. Of course, structural mass can also be reduced by lowering the pressure of the gas. Both possibilities turn out to be useful.

A Rotating System With 1 g at Less Than 1 rpm

Rotation is the only feasible way to provide artificial gravity in space. Pseudogravity depends upon both rotation rate and radius of rotation, and figure 4-4 shows the lines of constant pseudogravity as functions of these two variables (ref. 7). On the graph are shown a number of rotating systems: C-1 through C-4 are the rotating cylinders proposed earlier (ref. 1) by O'Neill; T-1 is a torus and S-1 is a sphere described later in this chapter; Arthur C. Clarke's Rama (ref. 4) is shown, as are space stations of Gray (The Vivarium) (ref. 8), Von Braun (ref. 2), and Tsiolkovsky (ref. 9). Obviously only systems with radii of rotation greater than 895 m can lie on the line g= 1 below 1 rpm.

An aluminum cylinder like C-3 would weigh about 42,300 kt and have a projected area of 55×10^6 m^2, enough to hold 800,000 people – rather than the 10,000 people of the design criteria. Similarly a sphere of radius 895 m would hold 75,000 people and weigh more than 3500 kt if made of aluminum.

A dumbbell shape has the advantage that the radius of curvature of the part holding the atmosphere can be made small while the radius of rotation remains large. However, in this configuration people could only live on the cross section of the spheres, and to hold 10,000 people with 670,000 m^2 of projected area the spheres would have to be 326.5 m in radius. Together they would weigh about 380 kt.

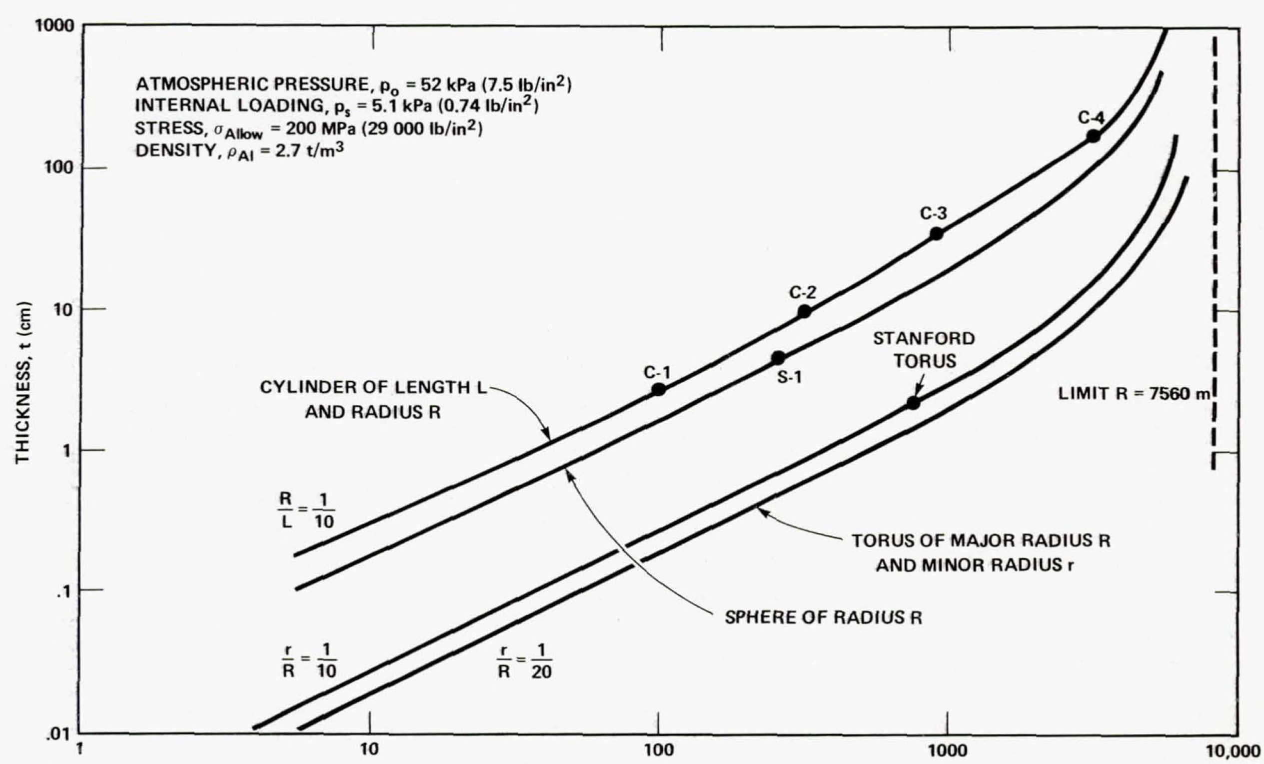

Figure 4-3.– *Shell thickness as a function of radius for spheres, cylinders, and toruses spinning to produce 1 g.*

A torus also permits control of the radius that contains the atmosphere separately from the radius of rotation. Moreover, the torus can distribute its habitable area in a large ring. Consequently, the radius needed to enclose the 670,000 m^2 of projected area can be quite small, with a correspondingly small mass – about 150 kt for a torus of major radius 830 m and minor radius 65 m (where the mass of internal structure is neglected). The advantages of the torus compared to the sphere and cylinder are discussed further in appendices B and C which define some criteria and parameters useful for such comparisons. The important point is that for a given radius of rotation about four times more mass is required to provide a unit of projected area in a cylinder or a sphere than in a torus of small aspect ratio. Thus, among the simple, basic shapes the torus is clearly superior in economy of structural mass.

If minimum structural mass were the only concern, composite structures would be the choice. Twenty-five pairs of dumbbells would supply 670,000 m^2 with spheres 65 m in radius and a total mass of 72 kt. The spheres could be made smaller still and formed into a ring to make a beaded torus. Alternatively, the toruses themselves could be made with quite small minor radii and either stacked and connected together to form a kind of banded torus, or built separately to form a group of small, independent habitats.

However, as pointed out in the previous chapter, it is desirable to compensate for the artificial and crowded nature of the habitat by designing it to give a sense of spaciousness. Composite structures are rejected largely on architectural criteria of environmental perception. Not only would they be more difficult to build than the simpler shapes, but also their short lines of sight, little free volume and internal arrays of closely-spaced cables and supporting members would produce an oppressive ambience.

If the colony were composed of a number of small structures, there would be problems of communication and transport between them as well as the drawbacks of small scale. Nevertheless, as table 4-1 shows, multiple structures (and composite ones too) offer substantial savings in mass, and it might well be that some of their undesirable aspects could be reduced by clever design. It would be an attractive option to be able to build up a colony gradually out of smaller units rather than to start off with an initial large scale structure. The subject of multiple and composite structures is worthy of more consideration.

The various properties of possible configurations are

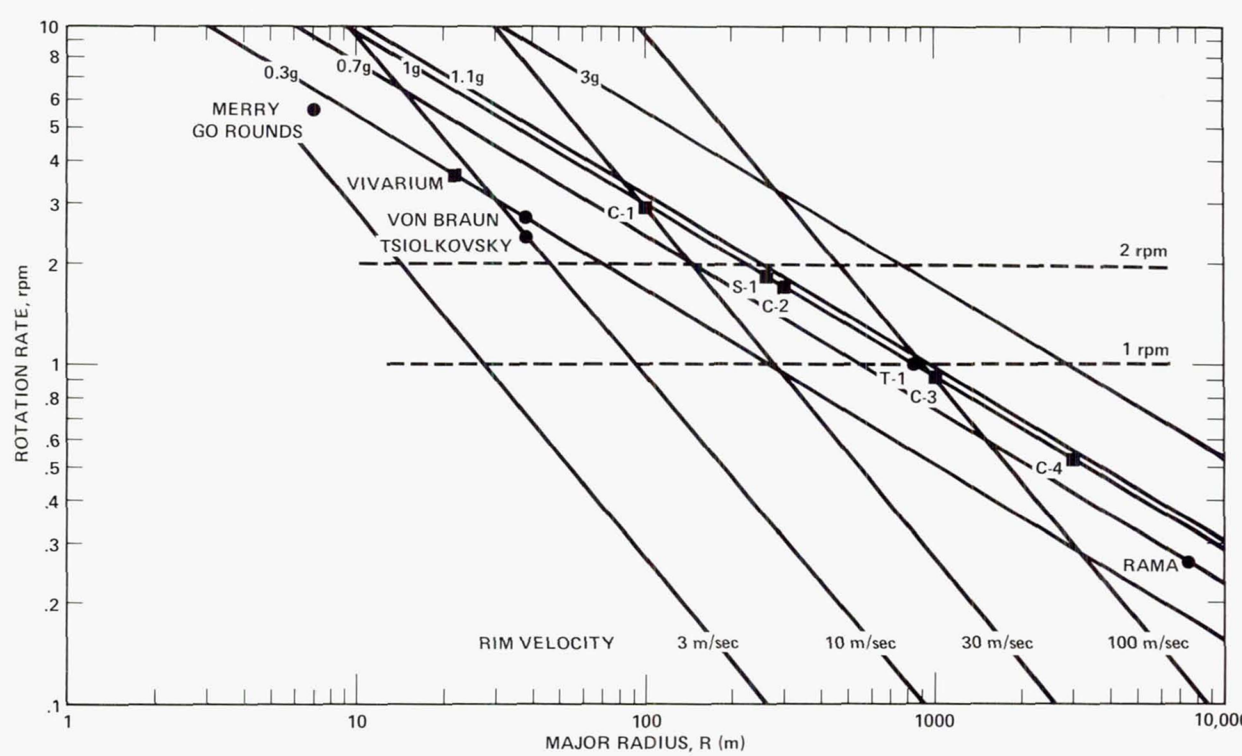

Figure 4-4.– *Properties of rotating habitat systems.*

summarized in table 4-1. The parameters show the mass requirements and indicate the degree of openness of the different structures. The single torus, although not the best design in many respects, seems to give the most desirable balance of qualities. Relative to the sphere and cylinder it is economical in its requirements for structural and atmospheric mass; relative to the composite structures it offers better esthetic and architectural properties. Because of its good habitability properties, large volume, a variety of possible internal arrangements, the possibility of incremental construction, a clear circulation pattern, access to zero gravity docks and recreation at the hub, agriculture as an integral part of the living area, and a clear visual horizon for orientation, the torus is adopted as the basic form of the habitat. The dimensions of this single torus are given in the first column of table 4-1.

SHIELDING

The need to shield humans adequately from the ionizing radiations of space imposed some significant design decisions. An ideal shield would bring the radiation dosage below 0.5 rem/yr cheaply and without impairing the contact of the colonists with their environment. However, after considering active shields which electromagnetically trap, repel or deflect the incident particles, and a passive shield which simply absorbs the particles in a thick layer of matter, the study group chose the passive shield for their design.

Active Shields

When a charged particle passes through a magnetic field, its path curves. Thus, as figure 4-5 shows, the proper configuration of magnetic field lines can form a shielded region which particles cannot enter. Since for a given magnetic field the curvature of the path of a particle is inversely proportional to its momentum, the region is shielded only against particles below a certain cutoff momentum or cutoff energy. Particles above this cutoff energy can still penetrate (ref. 10).

The problems of magnetic shielding become apparent when the cutoff energy has to be chosen. Protection against heavy ion cosmic rays, the so-called high-Z primaries (i.e. the iron nuclei and others mentioned in chapter 2) and most solar flares would be achieved with a cutoff of 0.5 GeV/nucleon. The difficulty is that most secondary particles are created from the primary flux above 2 GeV/nucleon which can penetrate the shield and generate secondaries in the mass of the shield itself. As a consequence a magnetic field around the torus with a cutoff of 0.5 GeV/nucleon and a structural mass of about 10 kt, corresponding to a thickness of matter of 0.5 t/m^2, would actually increase the exposure to about 20 rem/yr. Only the addition of shielding to an extent of 1.3 t/m^2 could reduce the dosage to a level equivalent to there being no secondary particle generation by shielding, that is, about 8 rem/yr. Furthermore, even then a specially heavily shielded shelter would be required as

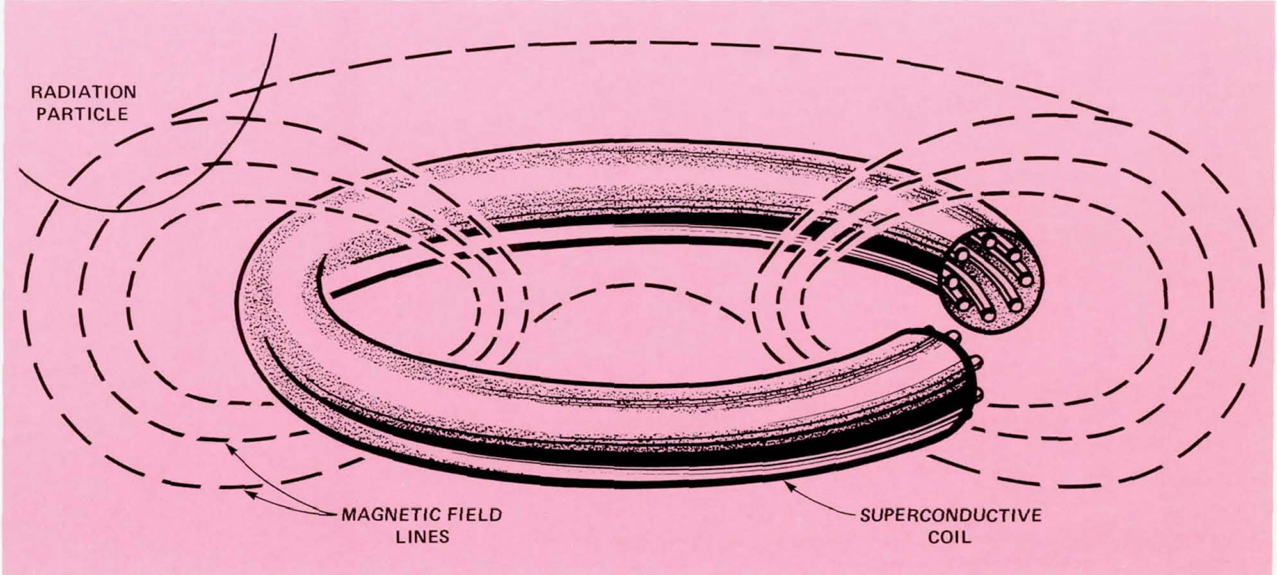

Figure 4-5.– *Magnetic shield around a torus.*

protection against secondaries produced by the strongest solar flares. The consequences of the production of secondary particles are shown in figure 4-6.

A cutoff of 10 or 15 GeV/nucleon would eliminate so many of the high energy particles that even with secondary production the dose would not be above 0.5 rem/yr. A shield of this capability would also protect against the effects of the strongest solar flares, and no shelter would be needed. The difficulty is that the structural mass required to resist the magnetic forces between superconducting coils precludes this design even for the most favorable geometry, namely, a torus.

Similarly, electric shielding by a static charge seems infeasible since a 10-billion-volt potential would be required for even moderate shielding. On the other hand, a charged plasma which sustains high electrical potential in the vicinity of the habitat is a more promising approach (ref. 11). However, means to develop such a plasma requires extensive research and technical development before a charged plasma might be considered for design. Some further details of this approach are given in appendix D.

Passive Shield

Passive shielding is known to work. The Earth's atmosphere supplies about 10 t/m^2 of mass shielding and is very effective. Only half this much is needed to bring the dosage level of cosmic rays down to 0.5 rem/yr. In fact when calculations are made in the context of particular geometries, it is found that because many of the incident particles pass through walls at slanting angles a thickness of shield of 4.5 t/m^2 is sufficient. Consequently it was decided to surround the habitat with this much mass even though it requires that many millions of tonnes of matter have to be mined and shipped to the colony.

TABLE 4-1.– PARAMETERS OF POSSIBLE HABITATS, 1 RPM

(a) Single component

	Single torus, R_{maj} = 830 m, R_{min} = 65 m	Cylinder with spherical endcaps, R = 895 m, L = 8950 m	Sphere, R = 895 m	Dumbbell, R = 895 m, R_{sphere} = 316 m
Number of components	1	1	1	1
Structural mass at 1/2 atm, kt	150	42,300	3545	380
Projected area, m^2	6.8×10^5	550×10^5	50.3×10^5	6.3×10^5
Surface area, m^2	2.1×10^6	60.3×10^6	10.1×10^6	2.5×10^6
Shielding mass, Mt	9.9	23.3	46.7	33.5
Volume, m^3	6.9×10^7	2265×10^7	300×10^7	13.2×10^7
Mass of atmosphere, kt	44	14,612	1930	85
Segmentation	Easy, optional	Difficult	Difficult	Difficult
Vistas:				
Longest line of sight, m	640	10,740	1790	732
Solid angle of 50 percent sight line, sr	0.5	0.09	4.2	4.2
Fraction of habitat hidden from view	0.70	0	0	0.5
Communication:				
Longest distance of surface travel, m	2600	11,800	2800	1800
Fraction viewable by internal line of sight from one place	0.3	1	1	0.5
Interior:				
Openness	Good	Good	Good	Good
Population capacity at 67 m^2/person	10,000	820,000	75,000	10,000

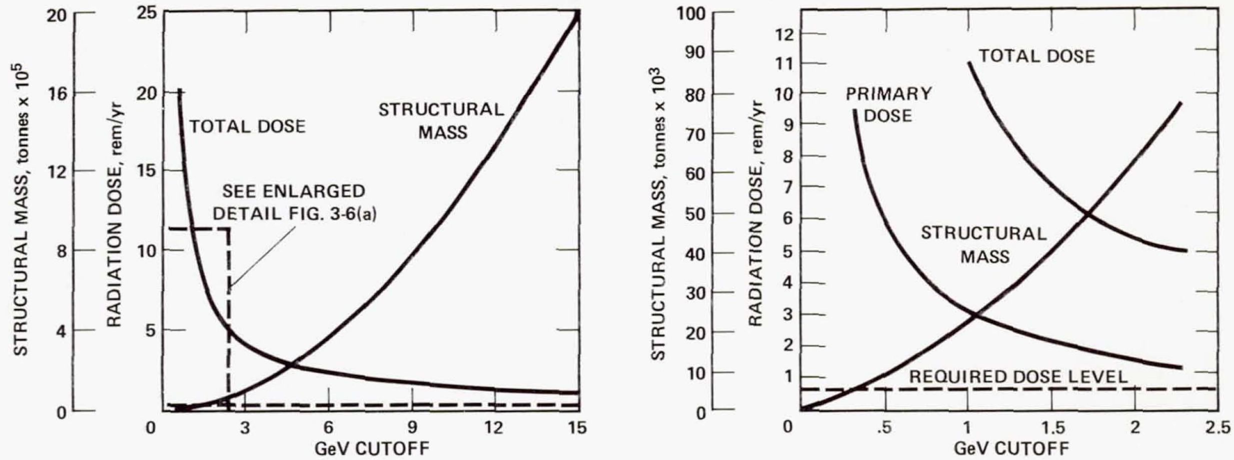

Figure 4-6.– *Magnetic shielding parameters – torus: $R = 900$ m; $r = 60$ m. This figure plots the structural mass of a magnetic cosmic ray shield as well as the annual radiation dose versus the shield's cutoff energy. The dose is derived from a rough calculation which includes spectrum cutoff, nuclear attenuation, secondary particle production, and self-shielding (50 g/cm^2 from body tissue and local mass concentrations). The dose calculated is probably uncertain by a factor of two. The essential reason why the dose declines so slowly with cutoff energy above 3 GeV is that the spectrum cutoff factor is cancelled, largely by secondary production in the shield's structural mass.*

TABLE 4-1.– Concluded

(b) Multiple components

	Multiple dumbbells, R_{sphere} = 65 m, R = 875 m	Multiple torus, R_{maj} = 880 m, R_{min} = 15 m	Banded torus, R_{major} = 880 m, R_{min} = 15 m
Number of components	25	4	1 (7 bands)
Structural mass at 1/2 atm, kt	72	100	112
Projected area, m^2	6.6×10^5	6.6×10^5	6.6×10^5
Surface area, m^2	2.7×10^6	2.1×10^6	1.7×10^6
Shielding mass, Mt	9.9	9.7	7.0
Volume, m^3	5.8×10^7	1.6×10^7	2.1×10^7
Mass of atmosphere, kt	37	10.4	13.2
Segmentation	Unavoidable	Unavoidable	Easy
Vistas:			
Longest line of sight, m	130	45	161
Solid angle of 50 percent sight line, sr	4.2	0.11	0.11
Fraction of habitat hidden from view	0.98	0.94	0.82 to 0.94
Communication:			
Longest distance of surface travel, m	1800	2600	2600
Fraction viewable by internal line of sight from one place	0.02	0.06	0.06
Interior:			
Openness	Poor	Poor	Poor
Population capacity at 67 m^2/person	10,000	10,000	10,000

Table 4-1 shows the shielding masses required for different configurations; the single torus requires 9.9 Mt of shield. This much mass cannot be rotated at the same angular velocity as the habitat because the resultant structural stresses would exceed the strength of the materials from which the shield is to be built. Consequently the shield must be separate from the habitat itself and either rotated with an angular velocity much less than 1 rpm or not rotated. To minimize the mass required, the shield would be built as close to the tube of the torus as possible, and therefore the rotating tube would be moving at 87 m/s (194 mph) past the inner surface of the shield from which it is separated by only a meter or two. The consensus of the study group was that the engineering necessary to assure and maintain a stable alignment between the moving torus and its shield would not, in principle, be difficult. However, no attention in detail was given to this problem.

WHAT IF THE CRITERIA CHANGE?

The conservative design criteria presently adopted for permanent life in space are derived from research on Earth and in space, especially Skylab missions, that gives very little indication of the actual effects of living in space for many years. In the time leading up to the colonization of space more information will become available, and it may lead to substantial changes in the configuration proposed in this study.

TABLE 4-2.– PARAMETERS OF POSSIBLE HABITATS WITH OTHER CRITERIA (EXTERNAL AGRICULTURE)

(a) Single components

	Single torus, R_{maj} = 209 m, R_{min} = 27 m	Cylinder with spherical endcaps R = 236 m, L = 2360 m	Sphere, R = 236 m	Dumbbell, R = 236 m, R_{sphere} = 33.3 m
Number of components	1	1	1	1
Structural mass at 1/2 atm, kt	4.6	775	64.6	0.4
Projected area, m^2	0.71×10^5	38.5×10^5	3.5×10^5	0.07×10^5
Surface area, m^2	2.2×10^5	42.0×10^5	7.0×10^5	0.28×10^5
Shielding mass, Mt	1.0	19.4	3.3	1.4
Volume, m^3	0.3×10^7	46.8×10^7	5.5×10^7	0.031×10^7
Mass of atmosphere, kt	1.9	299	35.2	0.20
Segmentation	Unavoidable	Difficult	Difficult	Unavoidable
Vistas:				
Longest line of sight, m	206	2800	470	67
Solid angle of 50 percent sight line, sr	0.9	0.09	4.2	4.2
Fraction of habitat hidden from view	0.65	0	0	0.5
Communication:				
Longest distance of surface travel, m	720	3100	740	540
Fraction viewable by internal line of sight from one place	0.35	1.0	1.0	0.5
Interior:				
Openness	Fair	Good	Good	Fair
Volume/area, m	42	121	157	44
Population capacity at 35 m^2/person	2000	110,000	10,000	200

Higher Population Density

A very simple change would be to reduce the amount of area available per person. Under these circumstances several of the structures described in table 4-1 would be made less massive. By placing the agriculture outside the shielded area and by reducing the remaining projected area available from 47 m^2 per person to 35 m^2, substantial savings could be made in both structural and shielding mass (table 4-2). This 25 percent increase in crowding may not be so drastic as it appears, since use can be made of the three dimensionality of space in a way more effective than is done on Earth. With sufficiently large overhead spaces between levels, several levels could be included in a habitat while maintaining an impression of openness. This approach would be particularly advantageous if the gravity criteria were relaxed as well.

Lower Simulated Gravity and Higher Rotation Rates

It is particularly interesting to examine the consequences of simultaneously relaxing the requirements of pseudogravity and rotation rate. If instead of 0.95 ± 0.05 g and 1 rpm, the design allows 0.85 ± 0.15 g and 1.9 rpm some interesting possibilities emerge. Under these new conditions, parameters for the same geometries discussed earlier are summarized in table 4-2. A major consequence is that the radius of rotation now becomes 236 m as figure 4-4 confirms.

TABLE 4-2.– Concluded

(b) Multiple components

	Multiple dumbbells, R = 236 m, R_{sphere} = 33.3 m	Multiple torus, R_{maj} = 209 m, R_{min} = 27 m	Banded torus, R_{maj} = 209 m, R_{min} = 27 m
Number of components	50	5	1 (8 bands)
Structural mass at 1/2 atm, kt	20	23.2	26
Projected area, m^2	3.5×10^5	3.6×10^5	3.6×10^5
Surface area, m^2	13.9×10^5	11.2×10^5	8.2×10^5
Shielding mass, Mt	7.2	5.2	3.6
Volume, m^3	1.5×10^7	1.5×10^7	1.8×10^7
Mass of atmosphere, kt	9.9	9.5	11.3
Segmentation	Unavoidable	Unavoidable	Easy
Vistas:			
Longest line of sight, m	67	100	100
Solid angle of 50 percent sight line, sr	4.2	0.9	0.9
Fraction of habitat hidden from view	0.99	0.93	0.9
Communication:			
Longest distance of surface travel, m	540	720	720
Fraction viewable by internal line of sight from one place	0.01	0.07	0.1
Interior:			
Openness	Good	Fair	Poor
Volume/area, m	43	42	50
Population capacity at 35 m^2/person	10,000	10,000	10,000

With this new radius of rotation neither a single torus nor a single dumbbell can supply sufficient space for a colony of 10,000. A cylinder, as before, supplies far too much. The sphere, on the other hand, supplies exactly the right amount and becomes an attractive possibility for a habitat. As the table shows, however, multiple and composite structures would still be contenders although they would be even more deficient in the desirable architectural and organizational features.

To be more specific, figure 4-7 illustrates a possible spherical design with the agriculture placed in thin toruses outside the shielded sphere. This configuration has been named the Bernal sphere in honor of J. D. Bernal (ref. 12). When the Bernal sphere is compared with its nearest competitor, the banded torus, it is seen to be particularly efficient in its shielding requirements, needing 300,000 t less than the banded torus and millions of tonnes less than any other configuration. The Bernal sphere, however, requires from 3 to 4 times as much atmospheric mass as the other possible forms, and from 2 to 4 times as much structural mass.

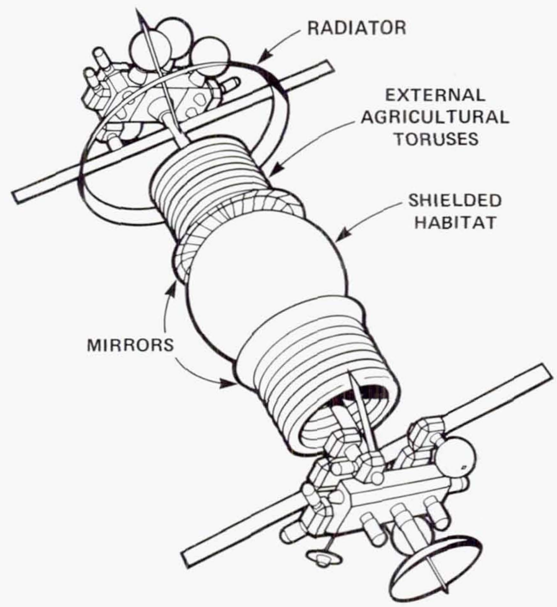

Figure 4-7.– *Schematic of a Bernal sphere configuration.*

Higher Radiation Exposures

As more is learned about the effects of ionizing radiation, it is possible that larger exposures to radiation might be found to be acceptable. Such a change in this criterion would make active magnetic shielding an interesting possibility and might also favor the development of a plasma shield. Of course, if higher levels of radiation became acceptable, a smaller amount of passive shielding would be needed so that the mass of shielding might become less significant in determining habitat design.

Any of these changes might shift the favored emphasis from one geometry to another. A choice of a particular form would again have to balance aesthetic against economic requirements, and it is certain that more investigation of this problem will be necessary. A particularly important question is the relative cost of shielding mass, structural mass, and atmospheric mass. Knowledge of these costs is basic to deciding which geometric alternative to select.

FABRICATION TECHNIQUES

Although the construction of large structures in space places strong emphasis on fabrication techniques, relatively little attention was devoted to the subject by the summer study group. The few alternatives considered did not seem to be mutually exclusive, but instead mutually supportive. Only a brief description of these alternatives is given.

Initial Construction Facilities

Fabrication facilities needed to build the habitat and supporting factories and power plants were described at a Princeton Conference, May 1975, on metal forming in space by C. Driggers. This proposal has been adopted. Standard technology for hot and cold working metals is sufficient to form the sheet, wire and structural members needed. An extensive machine shop must be provided so that many of the heavy components of a rolling mill, extrusion presses, casting beds and other equipment can be made at the space colony rather than have to be brought from Earth.

Building the Habitat Shell

Assembly of the habitat from aluminum plate and ribs proceeds first from the spherical hub (including docking facilities) outward through the spokes to start the torus shell. Both the spokes and shell are suitable for construction by a "space tunneling" concept in which movable end caps are gradually advanced along the tube as construction proceeds. This allows "shirt-sleeve" conditions for workmen as they position prefabricated pieces brought through the spokes and make the necessary connection. Large pieces of shield are placed around the completed portions as the slag material becomes available from the processing plant. Internal structures are built when convenient. However, every effort must be made to complete the basic shell and the first layer of shielding as quickly as possible so that spin-up can begin, gravity can be simulated, and the construction crew and additional colonists can move in to initiate life support functions within the habitat. A critical path analysis will reveal the best sequencing of mirror, power plant, shield, and internal construction.

An alternative technology for fabrication in space, which deserves more investigation, is the making of structures by metal-vapor molecular beams. This is discussed in more detail in appendix E. If proved out in vacuum chamber experiments, this technique may cut the labor and capital costs of converting raw alloys into structures by directly using the vacuum and solar heat available in space. Its simplest application lies in the fabrication of seamless stressed-skin hulls for colony structures, but it appears adaptable to the fabrication of hulls with extrusive window areas and ribs, as well as to rigid sheet-like elements for zero-gravity structures such as mirrors and solar panels.

A simple system might consist of a solar furnace providing heat to an evaporation gun, which directs a conical molecular beam at a balloon-like form. The form is rotated under the beam to gradually build up metal plate of the desired strength and thickness. While depositing aluminum, the form must be held at roughly room temperature to ensure the proper quality of the deposit.

Structures Inside the Habitat

To fulfill the criteria set forth in chapter 2, a lightweight, modular building system must be developed to serve as an enclosing means for the various spatial needs of the colony.

Modular building systems developed on Earth can be categorized into three general types: that is, box systems using room-size modules; bearing-panel systems; and structural-frame systems. A box system entails assembling either complete shells or fully completed packages with integrated mechanical subsystems. Bearing-panel systems use load-bearing wall elements with mechanical subsystems installed during erection. Structural-frame systems use modularized framing elements in combination with nonload-bearing wall panels and mechanical subsystems which are normally installed during erection. Other systems which have seen limited application on Earth but would be appropriate in the colony include: cable supported framing systems with nonload-bearing fabric and panel space dividers, and pneumatic air structures using aluminum foil and fiberglass fabrics with rigid, aluminum floor elements.

In selecting a baseline configuration, box systems were rejected because they normally involve the duplication of walls and floors and tend to be overly heavy. If metal vapor deposition is developed as a forming technique however, this type of system would become highly desirable. Bearing-panel systems were likewise rejected since they do not allow integration of mechanical subsystems except during erection, and since walls are heavy because they are load bearing. Cable and pneumatic systems were rejected due to their inability to span short distances without special provisions. However, they might be highly desirable because of their flexibility and lightness if a lower gravity environment proves acceptable in the colony.

The system that appears most suitable for use in the colony might involve a light, tubular structural frame (composed of modular column and beams) in combination with walls that are nonload bearing and with prepackaged, integrated mechanical subsystems (such as bathrooms) where needed. This system provides lightweight modularity to a high degree, good spanning capabilities, easily obtainable structural rigidity, and short assembly time since all labor intensive mechanical systems are prefabricated. A schematic (ref. 13) of some possible components of such a system is shown in figure 4-8. Applications of such a system to the colony are many and could be applied to all necessary enclosures with proper adaptation to the various specialized needs of life in space.

Some of the possible materials and components investigated as especially suitable for building in space are illustrated in appendix F. Elements that are light and strong and could be made from materials available in space are favored. The exterior and interior walls and the floor components are built from these materials. The floor components are based on extremely light yet strong elements designed for Skylab.

THE PEOPLE IN THE COLONY

It is not usual to think of human population as something to be designed. Nevertheless the numbers, composition, age and sex distribution, and productivity of the colonists bear importantly on the success of the project and on the creation of a suitable design. The study had to consider who should be the colonists, how many there should be, what skills they must have, and how they should organize and govern themselves. The alternatives are numerous and the grounds for choosing between them not as definite as for the more concrete problems of engineering, but it was possible to make what seem to be reasonable choices based on the goals of

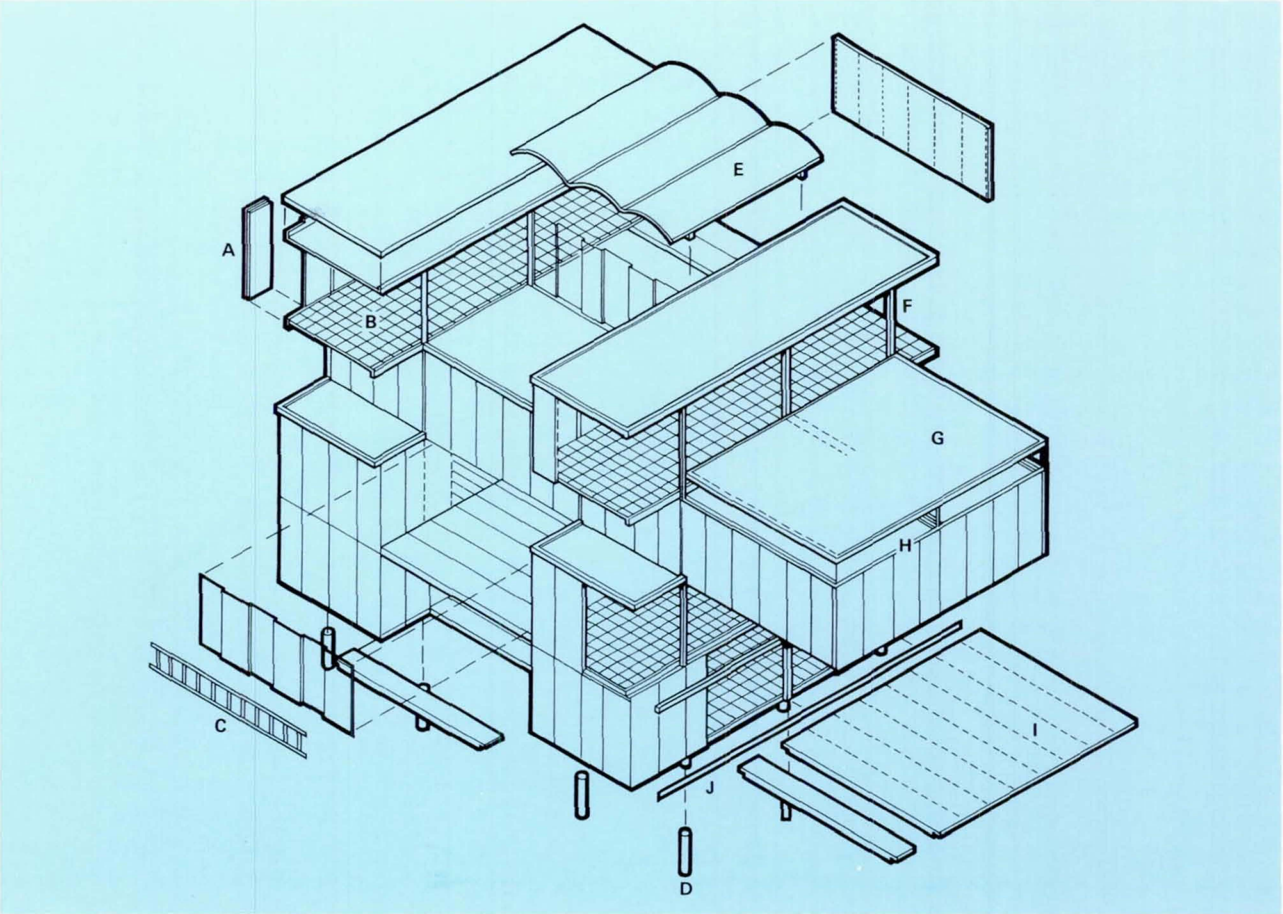

Figure 4-8.– *Modular construction for inside the habitat. This diagram illustrates the kinds of components which might be used in building the space colony. A. Wall panels, nonstructural, can be any material depending on acoustical, thermal, and stability requirements; B. floor construction light honeycomb panels; C. shades, railings, etc., added in place; D. structural supports – receives frame; E. "roofing" kits – translucent, clear or opaque, of various configurations; F. structural frame – stacks four stories, 1.82 m or 3.64 m X 5.46 m structural bay; G. roof panels – used where tops are intended for walking surfaces; H. ceiling panels – visual and thermal barrier; I. spanning planks or beams; J. beams. Source: Building Blocks Design Potentials & Constraints, Center for Urban Development Research, Cornell Univ., 1971.*

having in space permanent communities of sufficient productivity to sustain themselves economically.

Size and Suitability of Population

It is possible in principle to specify a productive task, for example, the manufacture of solar power satellites, and then calculate the number of people necessary to perform it, the number needed to support the primary workers, and the number of dependents. The sum of such numbers does not accurately define the population needed to found a colony since the calculation is complex. Even a casual consideration of what is necessary for a truly closed society would suggest that a colony population be far in excess of any reasonable first effort in space.

A similar approach would bypass the calculation just described and simply copy the population size and distribution of a major productive urban center on Earth. The difficulty, however, is that such communities are quite large, on the order of some hundreds of thousands of people. Moreover, close inspection reveals that human communities on Earth are less productive by labor force measurement standards than what would be needed in at least the early stages of space colonization.

One way to have a colony more productive than Earth communities would be to make the colony a factory, populated only by workers. The colony would

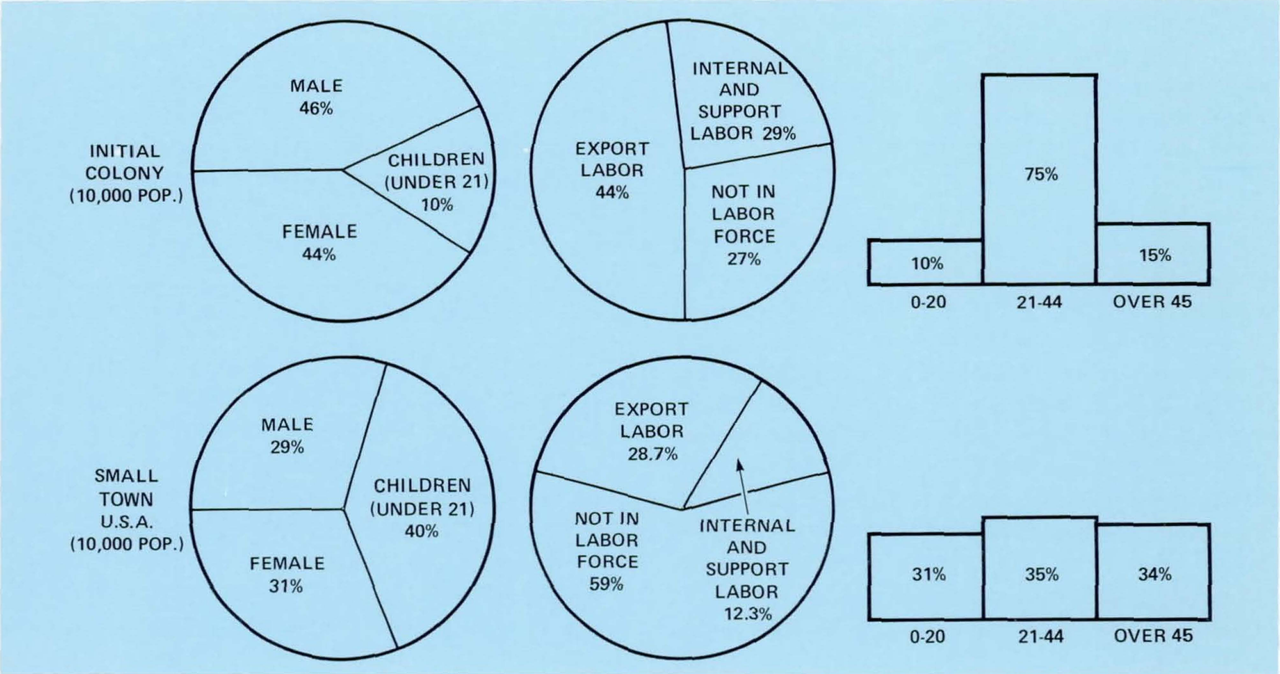

Figure 4-9.– *Population distributions of sex, age, and productive effort in the initial colony and in a similar sized community on Earth.*

then be only a space station, with crews of workers rotated in and out, much as is done on the Alaska pipeline project. Aside from the serious problems of transportation, such an approach does not meet the goal of establishing permanent human communities in space.

In the face of these difficulties a rather arbitrary decision is made to design for a colony of 10,000 with an attempt to bias the population in directions that favored high productivity but does not compromise too badly the goal of setting up a community in which families live and develop in a normal human way. It is also assumed that the completed colony is not an isolated single undertaking, but is a first step in a rapidly developing program to establish many colonies in space.

Ethnic and National Composition

The possible variations in nationality or ethnic composition are in principle very great. The actual composition will depend largely on who sponsors and pays for the colonization. If colonization were undertaken as a joint international project, the composition of the population would surely reflect that fact. On balance, however, it seems reasonable for the purposes of this design to assume that the first space colony will be settled by persons from Western industrialized nations.

Age and Sex Distributions

The initial population of the first colony is projected to grow from a pool of some 2000 construction workers who, in turn, bring immediate family members numbering an additional one to three persons per worker. Selective hiring of construction crew members tends to bias this population toward certain highly desirable skills, and toward the younger ages. In anticipation of the labor needs of the colony and the need to avoid the kinds of burdens represented by large dependent populations, a population is planned with a smaller proportion of old people, children and females than the typical U.S. population. It is a close analog of earlier frontier populations on Earth.

The proposed population is conveniently described in terms of differences from the population of the United States as described in the 1970 Census (ref. 14). These changes are illustrated in figure 4-9 which compares the colony with the composition of a similar sized community on Earth. The sex ratio is about 10 percent higher in favor of males, reflecting both the tendency of construction workers to be male and the expectation that by the time construction begins in space an appreciable fraction of terrestrial construction workers are female. Partly for this last reason and partly because of the anticipated need for labor in the colony, sizable increase in the proportion of married women in the labor force is assumed. Most striking is the substantial shift of the population out of the more dependent ages – from under 20 and over 45 into the 21 to 44 age class.

Export Workers

Productivity of any community is importantly influenced not only by the size of the labor force but also by the share of worker output going for export. Numbers on modern U.S. communities (see, e.g., appendix G) indicate that in our complex society the percentage engaged in export activity is generally less in the larger cities than in the smaller towns. The maximum activity for export seems to be about 70 percent. Without taking into account the peculiarities of life in space, the study group assumes that 61 percent of the workforce, or nearly 44 percent of the population of the initial colony would be producing for export (see fig. 4-9). This percentage declines as the colony grows. Conversely at an early stage in its development when the population is about 4300, the workforce is about 3200, with 2000 producing for export. Appendix G provides the data from which these assumptions are derived.

Social Organization and Governance

The form and development of governance depend strongly on the cultural and political backgrounds of the first colonists. The subject is rich with possibilities ranging from speculative utopian innovations to pragmatic copies of institutions existing on Earth. Among the alternatives easily envisioned are quasimilitary, authoritarian hierarchies, communal organizations like kubbutzim, self-organized popular democracies operating by town meetings, technocratic centralized control, or bureaucratic management similar to that of contemporary large corporations.

It seems most likely that government for the initial colony would be based on types of management familiar in government and industry today. There would be elements of representative democracy, but the organization would surely be bureaucratic, especially as long as there is need for close dependency on Earth. But whatever the forms initially, they must evolve as the colonists develop a sense of community, and it is easy to imagine at least two stages of this evolution.

First there is the start of colonization by some Earth-based corporate or governmental organization. Later, as continued development leads to more and more settlement, the colonists form associations and create governance bodies which reflect rising degrees of community identity, integration and separation of decision-making powers from organizations on Earth. These changes evolve first within a single habitat and then cooperative and governmental relations develop when neighboring habitats and a larger community grow. The rate at which this evolution occurs is uncertain.

LIFE SUPPORT

What do the colonists eat and how do they obtain this food? What do they breathe? How do they deal with the industrial and organic wastes of a human community in space? These questions pose the basic problems to be solved by life support systems. Richness of life and survival from unforeseen catastrophes are enhanced by diversification and redundance of food supplies, energy sources, and systems for environmental control, as well as by variety of architecture, transportation and living arrangements, and these considerations are as important in choosing among alternatives for life support as in making choices among other subsystems.

Food

Food supplies can be obtained from Earth or grown in space or both. Total supply from the Earth has the advantage that the colony would then have no need to build farms and food processing facilities or to devote any of its scarce labor to agriculture. However, for a population of 10,000 the transport costs of resupply from Earth at 1.67 t/yr per person is about $7 billion/yr. The preferred choice is nearly complete production of food in space.

Whatever the mode of production, it must be unusually efficient, thereby requiring advanced agricultural technologies (ref. 15). Direct synthesis of necessary nutrients is one possibility, but such biosynthesis is not yet economically feasible (J. Billingham, NASA/Ames, personal communication).[1] Also, algae culture and consumption have long been envisioned as appropriate for life in space, but upon close inspection seem undesirable because algae are not outstandingly productive plants nor are they attractive to humans (ref. 16). The best choice seems to be a terrestrial type of agriculture based on plants and meat-bearing animals (ref. 17).

This form of agriculture has the advantage of depending on a large variety of plant and animal species with

[1]Synthetic Carbohydrates, Summer Study Report, NASA-Ames Research Center.

the accompanying improvement in stability of the ecosystem that such diversity contributes (ref. 18). Moreover, plants and animals can be chosen to supply a diet familiar to the prospective colonists, that is, a diet appropriate to a population of North Americans biased in favor of using those plant and animal species with high food yields. Photosynthetic agriculture has a further advantage in that it serves as an important element in regeneration of the habitat's atmosphere by conversion of carbon dioxide and generation of oxygen. It also provides a source of pure water from condensation of humidity produced by transpiration (ref. 19).

Choices of food sources within the general realm of terrestrial agriculture become a compromise between preference and diversity on the one hand and efficiency on the other. For the colony, efficient use of area (even at expense of efficiency measured in other terms, i.e., as energy) is a critical factor to be balanced against a varied and interesting diet. For example, the almost exclusive use of rabbits and goats for animal protein previously proposed (ref. 15) for space colonies is rejected as being unnecessarily restrictive and seriously lacking in variety.

Recycling Wastes

High costs of transportation place great emphasis on recycling all the wastes of the colony. Because in the near future Earth appears to be the only practical source of elements fundamental to agriculture – carbon, nitrogen, and hydrogen – they must initially be imported from Earth. To avoid having to continually import these elements, all wastes and chemicals are recycled with as small a loss as possible.

Waste water can be treated biologically as in most terrestrial communities, physiochemically, by dry incineration, or by some more advanced technique such as electrodialysis, electrolysis, vapor distillation or reverse osmosis (ref. 20). Each of these alternatives is ruled out for various reasons. Biological treatment provides only incomplete oxidation and produces a residual sludge which must then be disposed of with attendant risks of biological contamination. Physiochemical treatment has no organic conversion, and is chemically a difficult process. Dry incineration requires an external energy source to maintain combustion and it produces atmospheric pollutants. All the advanced processes are incomplete in that the resulting concentrates require further treatment.

Wet oxidation (Zimmerman process) has none of the foregoing defects. Operating at a pressure of 10^7 MPa (1500 lb/in.^{2}) and a temperature of 260°C, wet oxidation with a total process time of 1-1/2 hr produces a reactor effluent gas free of nitrogen, sulfur and phosphorous oxides; a high quality water containing a finely divided phosphate ash and ammonia. Both the reactor gas and the water are sterile (refs. 21,22). At solids concentrations greater than 1.8 percent the process operates exothermally with an increase in the temperature of the waste water by 56° C (personal communication from P. Knopp, Vice-President, Zimpro Processing, Rothschild, Wisconsin). These definite advantages lead to the choice of this process as the basic technique for purification and reprocessing within the space colony.

Composition and Control of the Atmosphere

The desired composition of the atmosphere is arrived at as the minimum pressure needed to meet the criteria for atmospheric safety stated in chapter 2. This results in the atmospheric composition detailed in table 4-3. Its outstanding features are: normal terrestrial, partial pressure of oxygen, partial pressure of carbon dioxide somewhat higher than on Earth to enhance agricultural productivity, and a partial pressure of nitrogen about half of that at sea level on Earth. Nitrogen is included to provide an inert gaseous buffer against combustion and to prevent certain respiratory problems. Because nitrogen must come from the Earth, its inclusion in the habitat's atmosphere means there is a substantial expense in supplying it. This fact, in turn, suggests that it is desirable to hold down the volume of atmosphere in the habitat, a factor taken into consideration in the discussion of the habitat geometry given earlier. The total atmospheric pressure is thus about half that at sea level on Earth.

Atmospheric oxygen regeneration and carbon dioxide removal are by photosynthesis using the agricultural parts of the life support system. Humidity control is achieved by cooling the air below the dewpoint, condensing the moisture and separating it. Separation of condensate water in zero gravity areas (such as the manufacturing

TABLE 4-3.– HABITAT ATMOSPHERE

$T = 20 \pm 5°$ C

Relative humidity = 50 ± 10 percent

Gas	(kPa)	(mmHg)
O_2	22.7	170
N_2	26.6	200
CO_2	<0.4	<3
Total pressure	50.8	380
Water vapor	1.0	7.5

1 standard atmosphere = 101 kPa

area and hub) by hydrophobic and hydrophilic materials offers the advantage of a low pressure drop and lack of moving parts (ref. 23) and is the preferred subsystem.

Trace contamination monitoring and control technology is highly developed due primarily to research done in submarine environments. The habitat environment is monitored with gas chromatograph mass spectrometer instruments (ref. 24). Trace contamination control can be effectively accomplished by sorbtion (e.g., on activated charcoal), catalytic oxidation, and various inert filtering techniques.

SATELLITE SOLAR POWER STATIONS: NO ALTERNATIVES

An important goal for the design for space colonization is that it be commercially productive to an extent that it can attract capital. It is rather striking then that the study group has been able to envision only one major economic enterprise sufficiently grand to meet that goal. No alternative to the manufacture of solar power satellites was conceived, and although their manufacture is likely to be extremely valuable and attractive to investors on Earth, it is a definite weakness of the design to depend entirely on this one particular enterprise. A number of valuable smaller scale manufactures has already been mentioned in chapter 2 and, of course, new colonies will be built, but these do not promise to generate the income necessary to sustain a growing space community.

There is some choice among possible satellite solar power stations (SSPS). Two major design studies have been made, one by Peter Glaser of Arthur D. Little, Inc. (ref. 25), and the other by Gordon Woodcock of the Boeing Aircraft Corporation (ref. 26). Conceptually they are very similar, differing chiefly in the means of converting solar power to electricity in space. Woodcock proposes to do this with conventional turbogenerators operating on a Brayton cycle with helium as the working fluid; Glaser would use very large arrays of photovoltaic cells to make the conversion directly.

There is not a great deal to argue for the choice of one system rather than the other, except perhaps that the turbogenerator technology proposed by Woodcock is current, while Glaser relies on projections of present day photovoltaic technology for his designs. In the spirit of relying on current technology, the Woodcock design seems preferable, but a definite choice between the two is not necessary at this time. A more detailed description of the SSPS alternatives with a discussion of microwave transmission and its possible environmental impact is given in appendix H.

WHERE THE COLONY SHOULD BE LOCATED

Chapter 2 surveyed space and described what is there and how space is shaped in terms of distance, propulsive effort and gravitational attraction. These aspects of space together with the location of needed resources are important to choosing a site for the habitat. The community should be located for convenience with respect to its resources – sunlight, weightlessness, and minerals – and also with access to and from its principal market, Earth. The site should be chosen by balancing the needs of production against the needs of marketing the product.

Near to but not on the Moon

The minerals of space are to be found in the distant outer planets, the asteroids, the nearer and more accessible planets like Mars, the moons of other planets, or our own Moon. Of course the Earth is a primary source of mineral wealth too. It seems reasonable to place the colony near one of these sources. For reasons explained in the next section, the Moon is chosen as the principal extraterrestrial source of minerals, hence the habitat should be near the Moon.

But where should the habitat be placed in the vicinity of the Moon? At first glance the Moon's surface seems a good choice, but any part of that surface receives the full force of the Sun's radiation only a small fraction of the time. Moreover, on the Moon there is no choice of gravity; it is one-sixth that of Earth and can only be increased with difficulty and never reduced. Space offers both full sunshine and zero gravity or any other value of simulated gravity one might choose to generate. An additional difficulty with a lunar location is related to the major product of the colonies, SSPS's. Transporting them from the Moon to geosynchronous orbit is not economically viable. For ease of exploitation of the properties of space, the habitat should be located in free space.

In Free Space at L_5

Although there is no stable location at a fixed point in space in the Earth-Moon system, the colony could be located in any one of a number of orbits in free space. These orbits can be around the Earth, or the Moon, or both the Earth and the Moon. Those near either the Earth or the Moon are rejected because of the frequency and duration of solar eclipses which deprive the colony of its light and energy. Large orbits around the Earth make it difficult to deliver the large mass of material needed from the Moon, while large orbits around the Moon become orbits in the Earth-Moon system about which little is known at the present time. These last two options, while not chosen, present interesting alternatives which should be examined more closely.

There remain the orbits about the five libration points. Three of these, L_1, L_2, and L_3, are known to be unstable, and to maintain orbits around any of these three points for long periods of time requires appreciable expenditures of mass and energy for station keeping.

There do exist, however, large orbits around both of the remaining libration points, L_4 and L_5. These have been shown to be stable (refs. 27,28). A colony in either of these orbits would be reasonably accessible from both Earth and Moon. One of these libration points, L_5, is chosen for the location of the first space colony. This choice is somewhat arbitrary for the differences between L_4 and L_5 are very slight.

MINING, TRANSPORT, AND PROCESSING IN SPACE

From where will come 10 million tonnes of matter needed to build a colony? And where and how will it be processed, refined and shaped into the metals, glass and other necessary structural material? The topography of space shapes the answer to the first question; human ingenuity offers answers to the second. A major problem only partly solved is how to transport large quantities of matter from mines on the Moon to space. Some possible solutions to that problem are suggested.

Sources

As noted previously, lunar materials have been chosen to supply the great bulk of mass necessary for the first colony, including the shell and internal structure, passive shield, soil, and oxygen. As indicated in figure 4-10, only a small percentage of the mass, including initial structures, machinery, special equipment, atmospheric gases other than oxygen, biomass, and hydrogen for water, comes from Earth.

This decision has been made for a variety of reasons. Of the bodies in the solar system which might supply materials, the other planets are eliminated by the expense of transportation from their surfaces, and the moons of the outer planets by transport times of years and by costs. This leaves the asteroids, comets, and the moons of Mars.

While the composition of the moons of Mars is unknown, both the comets and asteroids are apparently abundant sources of organic materials in addition to rock and possibly nitrogen and free metals as well. For immediate future applications, however, the Moon's position makes it attractive and, compared to the asteroids, the Moon has advantages of known properties, a distance suitable for easy communication, and it allows perhaps simpler overall logistics.

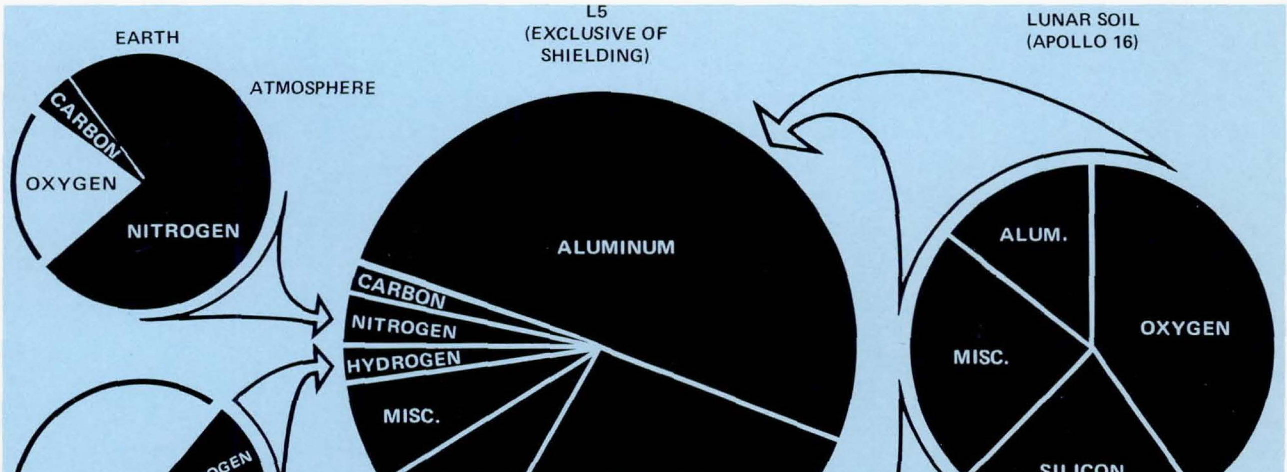

Figure 4-10.– *"Sources of Materials" pie chart of resources and their locations relative to L_5.*

However, when the space colonization program is begun, technical and economic imperatives seem likely to drive it quickly toward exploitation of asteroidal rather than lunar materials and toward much less dependence on Earth. Long before the results of mining activity on the Moon became visible from the Earth, the colony program would be obtaining its materials from the asteroids. Given that source, the "limits of growth" are practically limitless: the total quantity of materials within only a few known large asteroids is enough to permit building space colonies with a total land area many thousands of times that of the Earth.

Processing: Where?

A variety of alternatives exist for the processing of lunar ores to yield materials for the colony. These involve various combinations of processing site, materials to be produced, and chemistry. Optimization requires a detailed analysis of manifold possibilities. The study limited itself to choosing a plan which seems achievable and advantageous based on reasonable extrapolations of current technology.

The decision as to whether to process at the colony or on the Moon is dictated by various factors. The lunar site has the advantage of being close to the ore source and having a gravity which might be used in some chemical processing. Lunar processing might be expected to decrease the amount of material to be shipped to the colony. However, closer examination reveals that the colony's shielding requirements exceed the slag production of the processing plant; hence, no transportation is saved by processing at a lunar site. Moreover, lunar processing also possesses certain definite disadvantages when compared to processing at the site of the colony. Plant facilities shipped from the Earth to the Moon require much greater transportation expense than for shipment to the colony site. In addition, solar furnaces and power plants are limited to a 50 percent duty cycle on the Moon. Without power storage this would curtail operations at a lunar processing site. Radiators for process cooling are less efficient and, therefore, larger when placed on the Moon, because they have a view of the Sun or of the hot lunar surface. Finally, even at only 1/6 of Earth's gravity, components of the plant have significant weight. On the Moon this requires support structure and cranes and hoists during assembly. But these are not needed if processing is done at the colony site. Based on these considerations, it appears that major processing should take place at the colony site.

Processing: What and How?

The colony requires various materials which are obtainable from the lunar soil. Silica is needed for windows and solar cells. Oxygen is the major component of the colony atmosphere and is required for manufacturing water. It is also a rocket propellant. Silica and oxygen are essential to the success of the colony and therefore must be extracted from lunar ore. However, there is some latitude for choice and optimization among the variety of metals available. Aluminum, titanium, magnesium and iron are all potential construction materials. Although aluminum is chosen as our basic structural material, a decision to refine titanium might have some special advantages. On the Moon, titanium is in the form of a magnetic mineral (ilmenite) which can, in theory, be easily separated from the bulk of the lunar ore. In addition, use of titanium for structure would result in significant savings in the total amount of refined material because, although more difficult to form and fabricate, its strength-to-mass ratio is greater than that of the other metals available. Since ilmenite is basically $FeTiO_3$, significant amounts of iron and oxygen can be extracted as byproducts.

These facts support a recommendation that the alternative of titanium refining should be studied in detail. Possible methods for refining titanium are presented in figure 4-11 and discussed in appendix I.

Most of the remaining metal oxides in the ore must be separated from one another by rather complex techniques before further refining of the metals. Aluminum is the only other metal which justifies detailed consideration. In addition to excellent structural properties and workability it has good thermal and electrical properties (see appendix A). It is chosen as the principal structural material only because information concerning titanium processing is somewhat less definite and, in particular, the magnetic separation technique for lunar ilmenite has not yet been demonstrated.

The various methods by which aluminum might be refined from lunar anorthosite are shown schematically in figure 4-12. The system chosen is melt-quench-leach production of alumina followed by high temperature electro-winning of aluminum from aluminum chloride. Alternative paths are discussed in appendix I.

To provide window areas for the space structure, glass is to be manufactured from lunar materials. Silica (SiO_2), the basic ingredient in glassmaking, is found in abundance on the Moon. However, another basic constituent, sodium oxide (Na_2O), which is used in the most common flat plate and sheet glass industrially

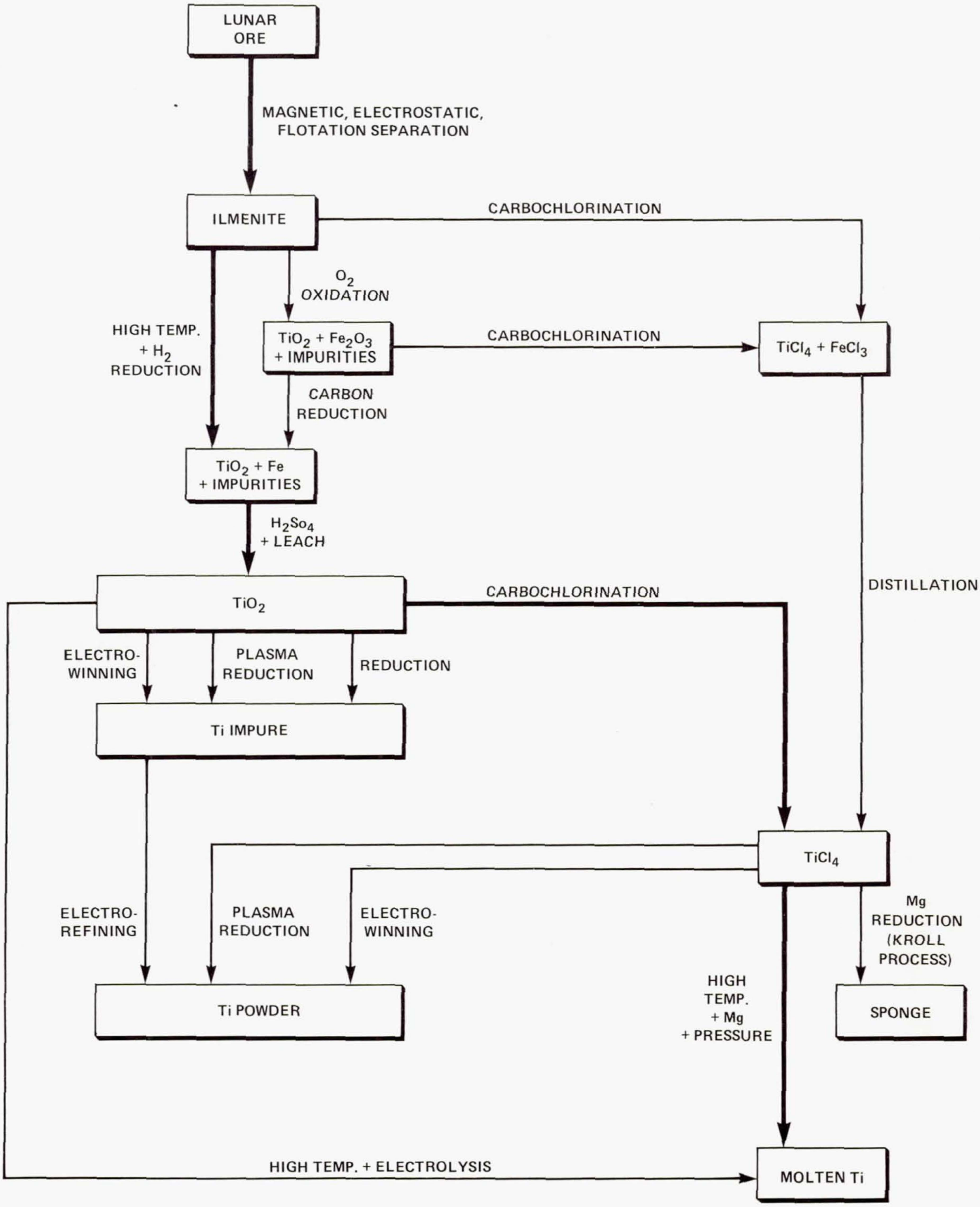

Figure 4-11.– *Summary of processes by which titanium can be extracted from ilmenite. Heavy line indicates the preferred process.*

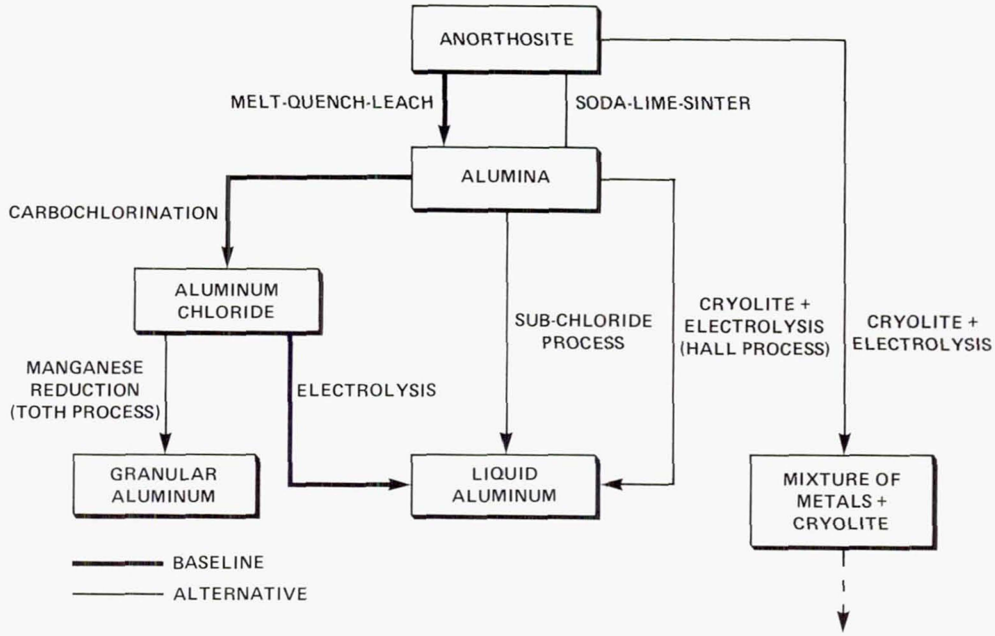

Figure 4-12.– *Processes by which aluminum can be extracted from anorthosite. Heavy line indicates the preferred process.*

produced, is found in only small percentages in the lunar soil. Glass processing on Earth uses Na_2O primarily to lower the melting temperature that has to be generated by the furnace (refs. 29,30). Since the solar furnace to be provided for processing the lunar material will be capable of generating temperatures considerably higher than those which could possibly be needed for this process, it appears unnecessary to supply additional Na_2O from the Earth (personal communication, J. Blummer, Vice-President for Research, Libbey Owens-Ford Company, Toledo, Ohio, Aug. 1975).

To date, glasses made from lunar soil samples returned by the Apollo missions have been dark in color. The techniques necessary to manufacture glass from lunar materials which possesses the properties needed for efficient transmission of sunlight into a space habitat have not been demonstrated (personal communication, Pittsburgh Plate Glass Company, Pennsylvania, Aug. 1975). However, it is believed that additional materials research will permit glass of adequate quality for a space facility to be processed from the lunar soil with a minimum of additives (if any) brought from the Earth (personal communication, D. R. Ulrich, Air Force Office of Scientific Research, Washington, D. C., Aug. 1975).

A possible technique which may prove feasible in space for large scale production is the removing of almost all nonsilicate ingredients by leaching with acid. Again, the availability of high furnace temperatures is a prerequisite to meet the melting temperature of silica, and the manufacturing process will have to be shown to be manageable in space. The resulting glass, of almost pure silica ($>$95 percent SiO_2), possesses the desirable properties of low thermal expansion, high service temperature, good chemical, electrical, and dielectric resistance, and transparency to a wide range of wavelengths in the electromagnetic spectrum.

Requirements for volume, mass, and energy of a glass-processing unit, a description of a sample process, and an elaboration of lunar soil constituents are given in appendix J.

Transport of Lunar Material

The construction of the colony depends critically on the capability of transporting great quantities of lunar material from the Moon to the colony without large expenditures of propellant. There are three parts to this problem: launching the material from the Moon, collecting it in space, and moving it to the colony. Two principal ways to launch have been devised, along with some variations.

One method is to launch large payloads, of about

60 t, by firing them from a large gas gun. The gun is operated by using nuclear power to compress hydrogen gas and then permitting the gas to expand the length of the launch tube. Because hydrogen must be obtained from Earth, its replacement is expensive, and consequently after each launch the gas is recovered through perforations in the end section of the launch tube which is encased in an enclosed tube. Further details are given in appendix K.

The system is of interest because of its conceptual simplicity and light weight. But the principal drawback of the gas gun system is the difficulty of collecting the payloads once they have been launched because their dispersion is large. Collection needs a fleet of automated interceptor rockets. The propellant requirement for interception is about 1 percent of the total mass launched. In terms of technology that may be available in the near future, these interceptor rockets have to use chemical propulsion with hydrogen as fuel. The second drawback is that the gas gun requires the development of sliding seals able to withstand high pressures and yet move at high velocities and still maintain acceptable leakage rates. Despite the uncertainties about precision of aim, the difficulties of automated rendezvous and interception, and the associated propulsion requirements, the concept appears fundamentally feasible and worthy of more study. However, the uncertainties are sufficient to make another alternative more attractive at this time.

The alternative method, which is the one chosen for this design, involves an electromagnetic mass accelerator. Small payloads are accelerated in a special bucket containing super conducting coil magnets. Buckets containing tens of kilograms of compacted lunar material are magnetically levitated and accelerated at 30 g by a linear, synchronous electric motor. Each load is precisely directed by damping the vibrations of the bucket with dashpot shock absorbers, by passing the bucket along an accurately aligned section of the track and by making magnetic corrections based on measurements using a laser to track the bucket with great precision during a final drift period. Alignment and precision are the great problems of this design since in order to make efficient collection possible, the final velocity must be controlled to better than 10^{-3} m/s. Moreover, the system must launch from 1 to 5 buckets per second at a steady rate over long periods of time, so the requirements for reliability are great. This system is considerably more massive than the gas gun. More details about it are given in the next chapter.

The problem of catching the material launched by the electromagnetic mass driver is also difficult. Three possible ways to intercept and gather the stream of material were devised. Two so-called passive catchers (described in more detail in appendix L), involve stationary targets which intercept and hold the incoming material. The other is an active device which tracks the incoming material with radar and moves to catch it. The momentum conveyed to the catcher by the incident stream of matter is also balanced out by ejecting a small fraction of the collected material in the same direction as, but faster than, the oncoming stream.

An arrangement of catching nets tied to cables running through motor-driven wheels permits rapid placement of the catcher anywhere within a square kilometer. By using a perimeter acquisition radar system, the active catcher tracks and moves to intercept payloads over a considerably larger area than the passive catchers. Unfortunately this concept, described in more detail in the next chapter, has the defects of great mechanical complexity. Nevertheless, although many questions of detail remain unanswered and the design problems appear substantial, the active catcher is chosen as the principal means of collecting the material from the mass launcher on the Moon.

Despite possible advantages it seems desirable not to place the catcher at the site of the colony at L_5. For three reasons L_2 is chosen as the point to which material is launched from the Moon.

First, the stream of payloads present an obvious hazard to navigation, posing the danger of damage if any of the payloads strike a colony or a spacecraft. This danger is particularly acute in view of the extensive spacecraft traffic to be expected in the vicinity of the colony. The payloads, like meteoroids, may well be difficult to detect. Hence, it appears desirable to direct the stream of payloads to a target located far from the colony.

Second, L_2 is one-seventh the distance of L_5, permitting use of either a smaller catcher or a less-accurate mass-driver.

Third, to shoot to L_5 requires that the mass-driver be on the lunar farside. For launch to L_2, the mass-driver must be on the nearside. By contrast, a nearside location for the mass-driver permits use of our knowledge of Moon rocks brought back in Apollo flights, and there are a number of smooth plains suitable for a mass-launcher. The nearside also permits line-of-sight communications to Earth.

Catching lunar material at L_2 means that transport must then be provided to L_5. It appears most practical to use mechanical pellet ejectors powered by an onboard nuclear system of 25 MW. This same system is used to offset the momentum brought to the catcher by the payloads arriving at up to 200 m/s.

THE TRANSPORT SYSTEM

The transportation requirements of a colony are much more extensive than merely getting material cheaply from the Moon to the factories of the colony. There must be a capability for launching about 1 million tonnes from the Earth over a total period of 6 to 10 years. There must be vehicles capable of traversing the large distances from Earth to L_5 and to the Moon. There must be spacecraft that can land equipment and people on the Moon and supply the mining base there. Fortunately, this is a subject to which NASA and the aerospace industry have given considerable thought; the study group relied heavily on this work. A schematic representation of the baseline transportation system is shown in figure 4-13.

From Earth's Surface to Low Orbit

The space shuttle is to be the principal U.S. launch vehicle for the 1980s. However for space colonization applications, the shuttle has low payload per launch and requires too many flights with excessive launch costs per kg. At the other end of the launch vehicle spectrum, a number of advanced concepts have been studied. These include a large winged "Super-Shuttle," fully-reusable ballistic transporters resembling giant Mercury capsules, and even use of a laser rocket with a remote energy source. Such concepts are not considered in this primary study because of uncertain technologies, excessive development costs, and long leadtimes. However, one concept for the "F-1 flyback" is discussed in appendix C of chapter 6.

The colony has to rely on lift vehicles derived from and, therefore, dependent on the shuttle and other already-developed boosters. Studies have been made on shuttle-derived heavy lift launch vehicles with two and with four solid boosters (fig. 4-14). In these, the manned shuttle vehicle is replaced with a simple vehicle having automated avionics and increased freight capability. The four-booster configuration has a payload of 150 t at under $20 million per launch.

A discussion of the environmental impact on the ozone layer of Earth by launch vehicles is given in appendix N.

Transport Beyond Low Earth Orbit

For routine transport of people and freight, the system uses single-engine vehicles employing space-storable, liquid-gas propellants in modular tankage. The NERVA nuclear rocket is rejected in favor of the space shuttle main engine (SSME). NERVA offers high performance but represents a new development, and involves the safety considerations associated with nuclear systems. The SSME represents an available, well-understood engine. Moreover, with oxygen for refueling available at L_5 from processing of lunar ores in industrial operations, the SSME vehicle performance would approach that of NERVA. Consequently the SSME as shown in figure 4-15 has been selected. Details are given in appendix M.

For passenger transport, the launch vehicle cargo fairing accommodates a passenger cabin holding 200 people. A single SSME could also be used to land over 900 t of cargo on the lunar surface.

For transport of major systems involving their own large power plants, electric propulsion is feasible. Such systems include the L_5 construction shack with its 300 MW power plant, and the solar-power satellites to be built at the colony for delivery to geosynchronous orbit. Candidate propulsion systems include ion rockets, resistojets, and mechanical pellet accelerators. In particular, for the baseline system, large numbers of standard ion thrusters are clustered, thus permitting application of current electric-propulsion technology. It is possible in the future that a Kaufman electrostatic thruster could be developed with oxygen as propellant. As described in the next chapter, a rotary pellet launcher is proposed to power the tug which brings the lunar ore from L_2 to the processing plant at L_5.

SUMMARY

Thus the system described in chapter 1 is arrived at. It carries 10,000 colonists in a toroidal habitat positioned at L_5 orbiting the Sun in fixed relation to the Earth and Moon and exploiting the paths through space in figure 4-16. Mining the Moon for oxygen, aluminum, silica, and the undifferentiated matter necessary for shielding, the colonists ship a million tonnes per year by electromagnetic mass launcher to L_2. There, with the active catcher, the material is gathered and transshipped to L_5 to be refined and processed. With small amounts of special materials, plastics, and organics from Earth, the colonists build and assemble solar power stations which they deliver to geosynchronous orbit. The colonists also raise their own food and work on the construction of the next colony. The following chapter gives a more detailed picture of how the various parts work together.

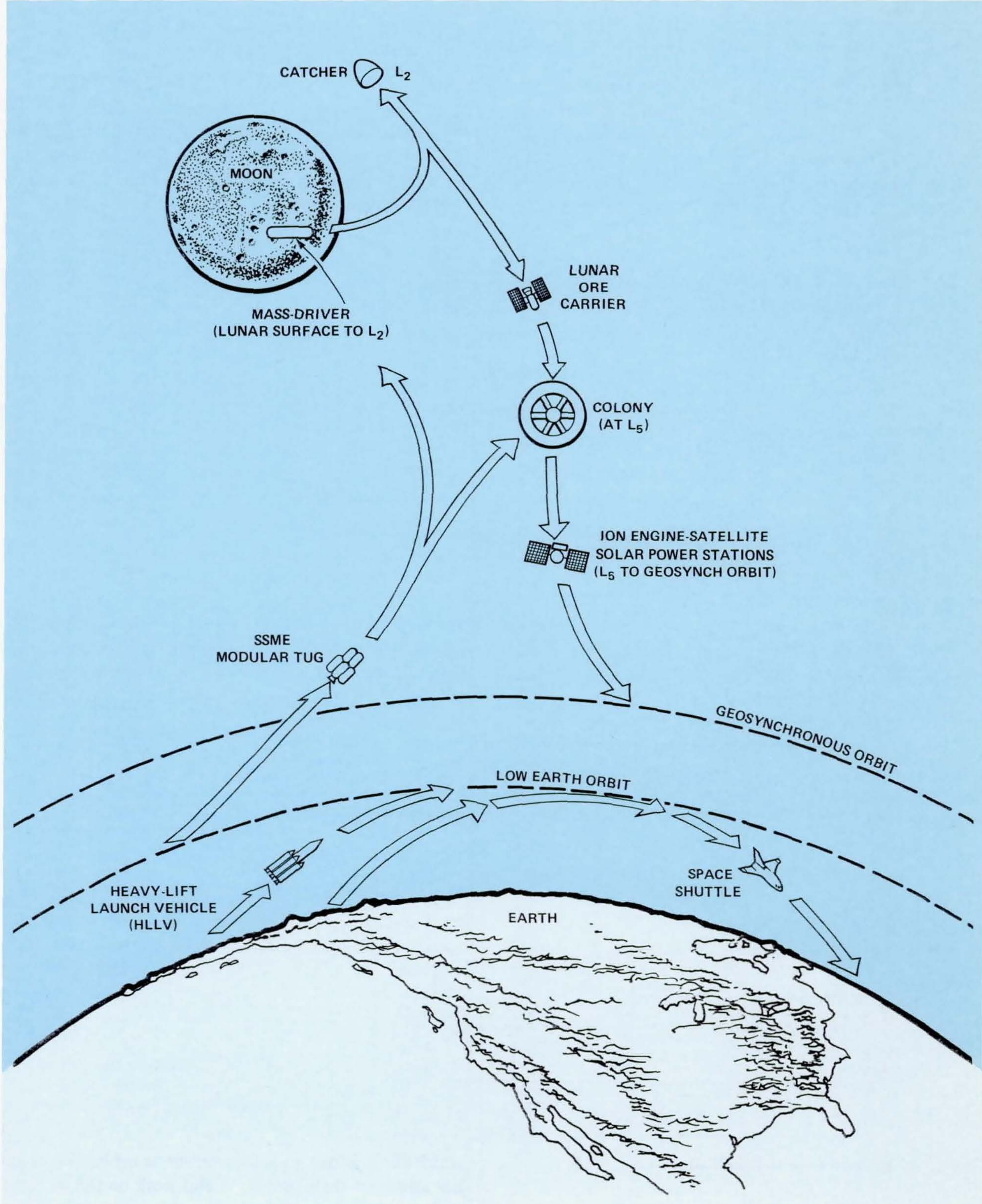

Figure 4-13.– *Baseline transportation system.*

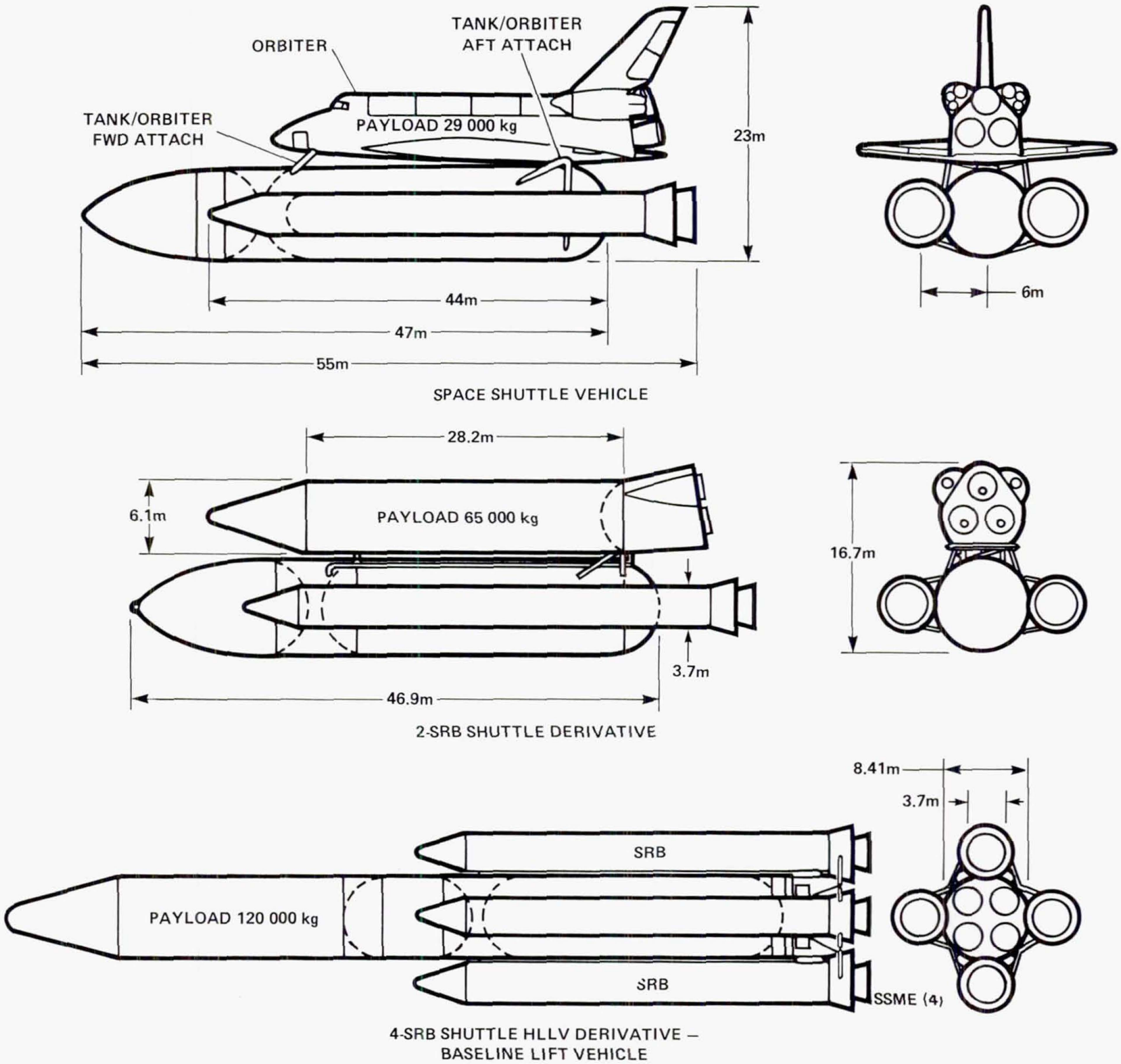

Figure 4-14.– *Shuttle derivatives for transport of people and goods from Earth to low orbit.*

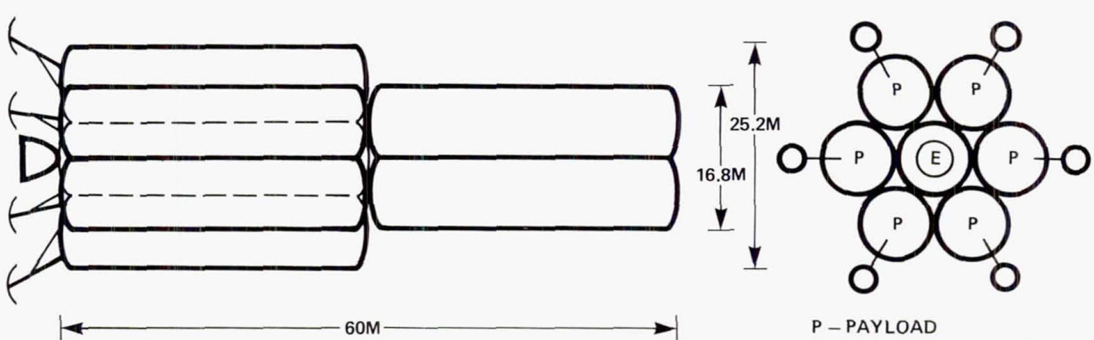

Figure 4-15.– *SSME powered modular tug.*

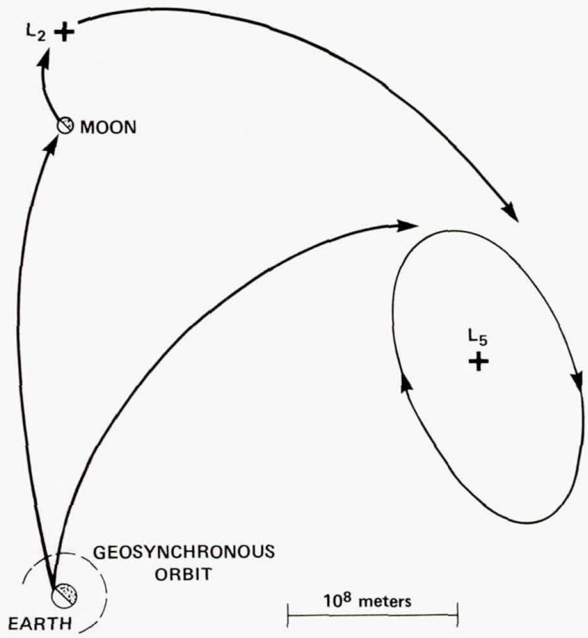

Figure 4-16.–*Paths through space for space colonization.*

APPENDIX A

MATERIAL PROPERTIES FOR DESIGN

To estimate the masses of components for alternate configurations, nominal design values for a variety of physical properties must be assumed for the materials involved. Only a few "standard" metal alloys are shown in table 4-4, chosen to give good weldability, corrosion resistance, and forming properties. A more careful specification of specific alloy percentages for structural components in a final design is expected to reduce the actual structural mass somewhat from that derived from this conservative approach. For particular applications where, for example, cyclic stress reversal may induce fatigue, high temperatures cause creep, or low temperatures cause brittleness, special materials must be used.

A safety factor of 1.5 is applied to the yield stress to give safe working values. This corresponds to the standard for large civil engineering structures combining dead- and live-load factors. In all large structures the material is proof-tested before use, so that, in reality, the end result of processing and fabrication is not a dubious variable but can be a controlled parameter. At least one

TABLE 4-4.– MATERIAL PROPERTIES OF SOME METAL ALLOYS

Metals type	Tensile strength			Brinell hardness number (500-kg load 10 mm diam ball)	Density G, 10^3 kg/m^3	Modulus E, MPa	Poisson ratio, ν	Coefficient of expansion α, 10^{-6} °C^{-1}	Conductivity	
	Ultimate σ_u, MPa	Yield σ_y, MPa	Working $\sigma_w = 2/3\,\sigma_y$, MPa						Electric, $10^{-6}\times$ ohm-m^{-1}	Thermal, W/m °C
Aluminum (150° C)										
i) Pure (99.5 percent)	83	41	28	30	2.70	70,000	1/3	24	36	230
ii) Heat treated alloy: Al 12 Si 0.5 Mg	303	248	165	95	2.65	76,000	1/3	19	21	157
iii) Cold formed wire or plate	455	352	234	140	2.65	76,000	1/3	20	31	163
Titanium										
i) Heat treated alloy: Ti 5 Al 2.5 Sn	620	517	345	105	4.54	110,000	1/3	10	---	22
ii) Cold formed wire or plate	1030	931	620	110	4.54	110,000	1/3	9	---	23
Magnesium										
i) Heat treated castings: Mg 8.5 Al	138	83	55	48	1.8	43,000	0.35	27	7	93
ii) Thin plate or wire Mg 3 Al 0.5 Mn 0.1 Zn	207	152	110	52	1.8	43,000	.35	25	8	81
Steel										
i) Wrought iron	352	207	138	70	7.8	207,000	.3	12	9	93
ii) Rolled - heat treated	538	352	234	120	7.8	200,000	.3	12	8	81
iii) Cold drawn	1380	1240	830	200	7.8	200,000	.3	12	8	81

good machine for static and dynamic testing of the strength of materials must be included in the laboratory equipment brought from Earth to the colony site.

The strength properties of ceramic-type materials and "soil" (table 4-5) are low, and experimental results from any pilot study for processing lunar ores should help define them more precisely. While it should also be possible to grow long glass fibers having great structural strength, such materials are not assumed for construction of the first colony.

TABLE 4-5.– MATERIAL PROPERTIES OF SOME CERAMICS AND SOILS

	Flexural working stress σ_W(tension),[a] MPa		Brinell hardness number (500-kg load 10 mm diam ball)	Density G, 10^3 kg/m^3	Poisson ratio, ν	Coefficient of expansion α, 10^{-6} °C^{-1}	Thermal conductivity, W/m °C
	Untempered	Tempered					
Ceramics							
i) Silica glass	3.4	6.9	400	2.2	0.18	80	15
ii) Window sheet	8.3	16.5	500	2.45	.23	850	.9
Rock							
i) Fused	3.4		200	2.8	.15	---	---
ii) Soil (dry)	---		---	1.4	.1	---	---
iii) Soil (60 percent moisture)	---		---	1.68	.5	---	---

[a]Compressive strength is about 10 times greater.

TABLE 4-6.– PROJECTED AREAS AND HABITABLE VOLUMES

Geometry	Projected area, Ap	Habitable volume, V_H
Cylinder	$2\pi RL$	$\pi R^2 L(2\gamma - \gamma^2)$
Sphere	$4\pi R^2(1-\gamma)\sqrt{2\gamma-\gamma^2}$	$2\pi R^3\gamma\left(1-\frac{\gamma^2}{3}\right)$
Cylinder and spherical endcaps	$2\pi RL + 4\pi R^2(1-\gamma)\sqrt{2\gamma-\gamma^2}$	$2\pi R^3\gamma\left[L\left(1-\frac{\gamma}{2}\right)+R\left(1-\frac{\gamma^2}{3}\right)\right]$
Torus	$4\pi rR$	$2\pi r^2 R\left(\frac{\pi}{2} - \sin^{-1}\left[1-\gamma\left(1+\frac{R}{r}\right)\right] - \frac{1}{2}\sin\left\{2\sin^{-1}\left[1-\gamma\left(1+\frac{R}{r}\right)\right]\right\}\right)$ for: $0<\gamma<\frac{2}{1+(R/r)}$; $2\pi^2 r^2 R$, all other γ.

$\gamma \equiv \Delta g/g$ $\quad$ r = minor radius of torus

R = radius of rotation $\quad$ L = length of cylinder

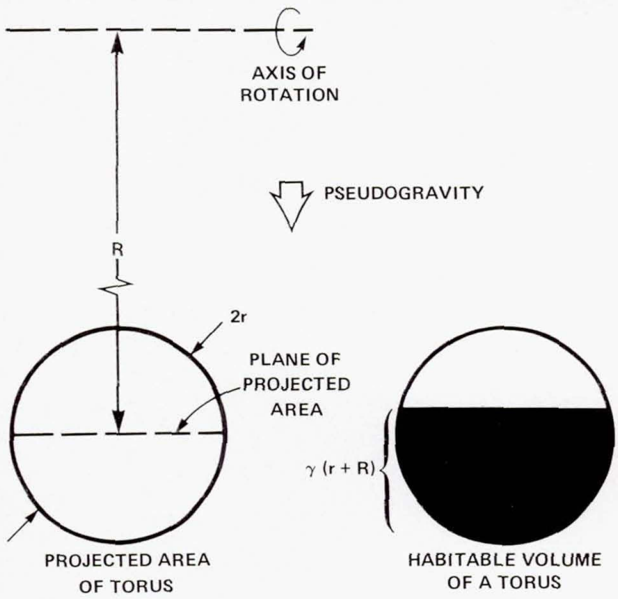

Figure 4-17.– *Projected areas of basic shapes.*

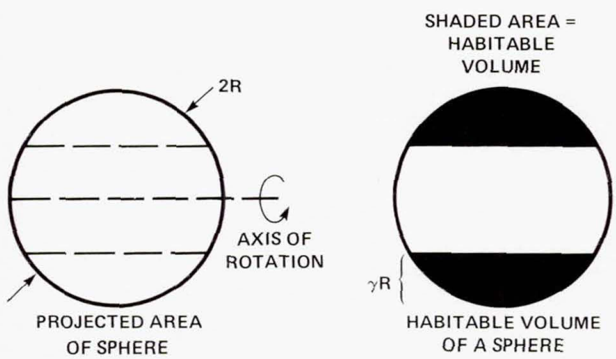

Figure 4-18.– *Habitable volume of a torus.*

APPENDIX B

PARAMETERS OF HABITABILITY

In a rotating habitat in space three factors affect the area and volume available for residence. Due to physiological considerations living and sleeping are confined for a large portion of the day to a volume where the change in pseudogravity, g, is less than some amount, Δg, which experience must determine. The habitable volume is that volume where $\Delta g/g$ is less than or equal to some number which the study group calls the habitability parameter, $\gamma = \Delta g/g$. It is not inconceivable, for example, that ways may be found to live safely and comfortably through the entire range from 0 to 1 g. In that case γ would equal 1, and the entire volume of the space colony is habitable.

Projected Area

City planners and architects design human habitation in terms of the surface area on which buildings may be constructed. In the kinds of habitats discussed in this study, the curvature of surfaces on which colonists might live is often pronounced. It seems reasonable to define available surface area as the projection of area onto a plane perpendicular to the direction of the pseudogravity. In a torus the projected area is a strip through the diameter of the tube of the torus (see fig. 4-17). If the minor radius is r and the major radius is R, the projected area for a torus is $A_{p_t} = 4\pi rR$.

This is just $1/\pi$ times the total skin area of a torus. Note that if the torus is spun so that there is 1 g of pseudogravity at the outermost surface, and if the aspect ratio, $\eta = r/R$, is greater than the habitability parameter, γ, the plane of projected area is outside the habitable volume. For all the cases considered, $\eta \leqslant \gamma$, and the above formula is sufficient.

For a rotating sphere the projected plane of usable area is the surface of a cylinder inscribed in the sphere (see fig. 4-18). The surface of this cylinder should not be more than γR above the surface of the sphere. The projected area then is

$$A_{p_s} = 4\pi R^2(1 - \gamma)\sqrt{2\gamma - \gamma^2} \ .$$

At $\gamma = 0.29$ this expression has a maximum $A_{p_s} = 2\pi R^2$. Consequently for $\gamma \geqslant 0.29$ the expression for the maximum can be used. (Alternatively, for smaller γ, the habitat might be spun to produce 1 g at $R/\sqrt{2}$ to maximize the available area).

For a cylinder of radius R and length L the projected area is just the surface area $2\pi RL$. Table 4-6 summarizes the expressions for projected area in different geometries.

Habitable Volume

Although projected area represents an important concept in conventional architectural thinking, the available volume in the habitat may be more relevant in specifying the apparent population density and the quality of life. Habitable volume is defined as that volume in which the pseudogravity does not vary more than the specified amount, Δg, from the nominal value of g. Consequently, habitable volume depends on $\Delta g/g$.

For a cylinder of length L and radius of rotation R, the habitable volume is the annulus between R and $(1 - \gamma)$R. In a sphere with a pseudogravity no greater than 1 g on its surface, habitable volume is the figure of revolution of the shaded area (as for the sphere in fig. 4-18).

In a torus with 1 g at its outermost circumference, habitable volume is the shaded area of the tube revolved around the axis of rotation. The formulas for these volumes are given in table 4-6.

Area and Volume Requirements

The study group determined that a reasonable standard of projected area is 67 m^2/person. Also, a detailed inventory of structures and facilities required for individual and community life suggests that habitable volume should be about 1740 m^3/person. Consequently, a habitat, or a collection of habitats, suitable for a given population of 10,000 people, must provide an area of 670,000 m^2 and a volume of 17,400,000 m^3. These numbers determine the geometry in a fundamental way.

APPENDIX C

MASS AS A MEASURE OF STRUCTURAL COST

Structural mass is an important measure of the effort and resources required to build a habitat. To compare the masses required to construct different geometries two questions must be answered: How much mass is required to obtain a given amount of projected area? How much mass is needed to get a given habitable volume?

Formulas for the structural masses for several different geometries are given in table 4-7 both for stressed skin and for ribbed construction. It is convenient to represent the sphere as a limiting case of a cylinder with spherical endcaps. To do this the aspect ratio, $\alpha = L/R$, is defined. It is also convenient to express the minor radius of the torus in terms of an aspect ratio $\eta = r/R$.

Mass Per Projected Area or
Per Habitable Volume for Different Geometries

From the formulas in tables 4-6 and 4-7, the mass required for a piece of projected area in a given geometry can be calculated. These tables also permit the mass per unit habitable volume to be determined.

It is convenient to compare different geometries by taking the ratio of their masses per projected area. The ratio of the mass per projected area for a cylinder with spherical endcaps to the mass per projected area for a torus (where for simplicity only stressed skin construction is considered) is given by:

$$\zeta_V = \frac{\left\{ \begin{array}{c} (\alpha + 1)[1 + (\Gamma/P_A)]\,\eta\Big[(\pi/2) - \sin^{-1}\{1 - \gamma[1 + (1/\eta)]\} \\ -(1/2)\sin\big(2\sin^{-1}\{1 - \gamma[1 + (1/\eta)]\}\big)\Big] \end{array} \right\}}{[\pi\eta + 2(\Gamma/P_A)]\,\gamma\,\{\alpha[1 - (\gamma/2)] + 1 - (\gamma^2/3)\}}$$

$$\sigma \leqslant \gamma \leqslant \frac{2\eta}{1 + \eta}$$

which is independent of R and g and, therefore, of rotation rate.

Figure 4-19 is a graph of the variation of this ratio for several configurations. Where $\alpha = 0$, a torus and a sphere are compared; whereas for $\alpha = 10$, the four models C-1

TABLE 4-7.– STRUCTURAL MASSES

Geometry	Stressed skin	Ribbed
Torus	$\dfrac{4\pi^2 GR^3\eta}{\sigma - GgR}\left(\dfrac{P_A\eta}{2} + \dfrac{\Gamma}{\pi}\right)$	$4\pi^2 GR^3\eta\left[\dfrac{(P_A\eta/2) + (\Gamma/\pi)}{\sigma - GgR} + \dfrac{P_A\eta}{\sigma}\right]$
Cylinder with endcaps	$\dfrac{2\pi GR^3}{\sigma - GgR}\left[(\alpha + 1)(P_A + \Gamma)\right]$	$\dfrac{2\pi GR^3}{\sigma - GgR}\left\{P_A\left[1 + \alpha\left(\dfrac{3}{2} - \dfrac{GgR}{2\sigma}\right)\right] + (\alpha + 1)\right\}$

G = density of structural materials
R = radius of rotation
σ = working stress
P_A = atmospheric pressure
Γ = internal load
g = pseudogravity
α = cylinder aspect ratio
η = torus aspect ratio

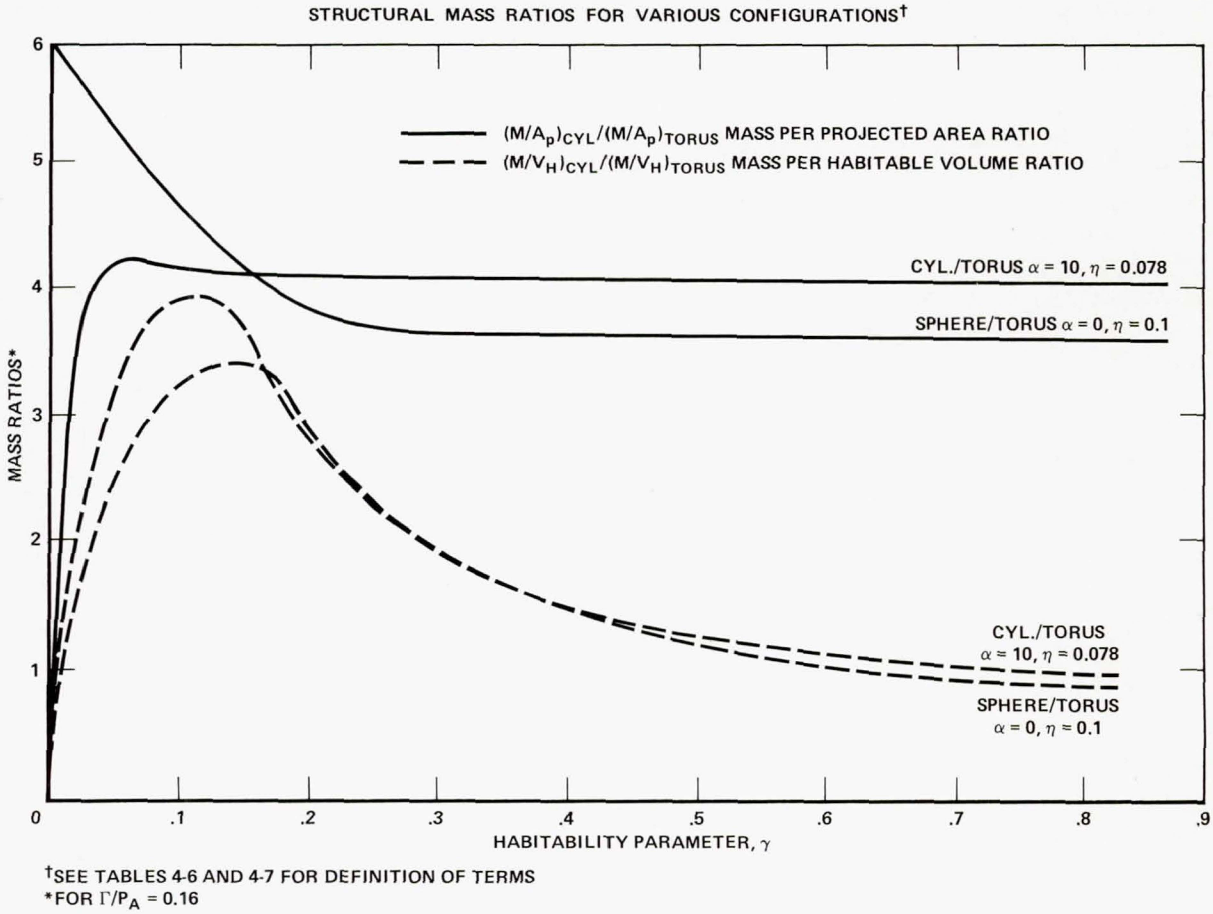

Figure 4-19.– *Mass per projected area and mass per habitable volume comparison for different geometries.*

to C-4 discussed by O'Neill (ref. 1) are compared to the corresponding toruses. In each case the internal load is taken to be 0.16 of the pressure of the atmosphere; the design figure in this study.

From tables 4-6 and 4-7 an expression can be derived for the ratio of the mass per habitable volume of a cylinder with spherical endcaps to the mass per habitable volume of a torus.

$$\zeta_V = \frac{\eta(\alpha + 1)\,[1 + (\Gamma/P_A)]\,\pi}{\gamma\{\alpha[1 - (\gamma/2)] + 1 - \gamma(3/3)\}\,[\pi\eta + 2(\pi/P_A)]},$$

where $\quad \gamma \geqslant \dfrac{2\eta}{1 + \eta}$

APPENDIX D

THE PLASMA CORE SHIELD

Cosmic ray shielding is needed for all human habitats in space. The obvious solution is to use mass as shielding, but mass is expensive. Thus if a different means of radiation protection is possible and is compatible with the other requirements of a productive habitat, it should be used. Such a possibility is offered by the class of devices called "plasma radiation shields" (ref. 31). However, these devices are speculative.

A plasma core shield is a variant of the plasma radiation shield discussed in reference 31. Figure 4-20 shows a toroidal habitat with an "electron well" at the hub. Inside this well about 10^3 C of electrons spiral along lines of magnetic force, and hold the metallic habitat at a

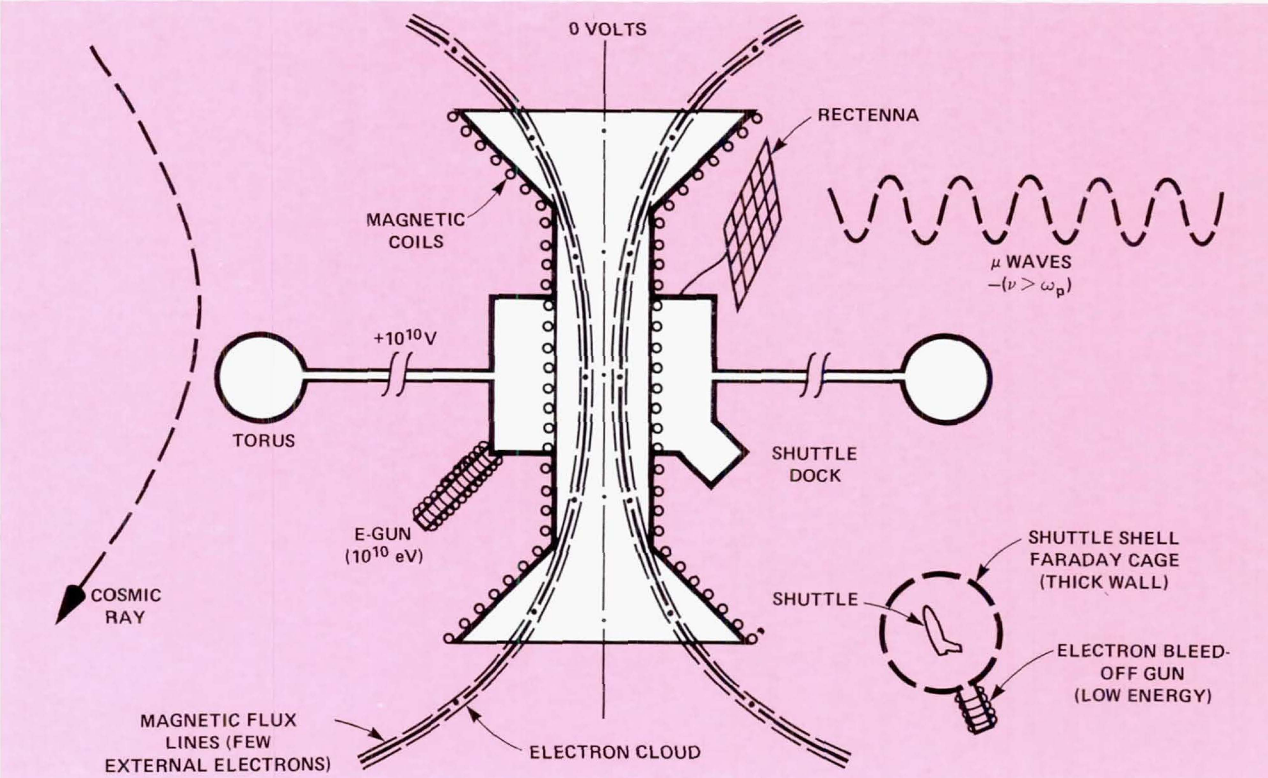

Figure 4-20.– *Solenoid core plasma shield.*

positive potential of 15 billion volts. The enormous electrostatic potential repels the protons and other cosmic ray nuclei from the habitat, and cuts off the cosmic ray spectrum for energies below 7.5 GeV/nucleon (15 GeV for protons). With this cutoff the net radiation dose, including secondary production, is below the acceptable dose of 0.5 rem/yr.

The critical advantage of the plasma core shield over earlier plasma shields is that the fringing fields at the lips of the electron well keep the electrons electrostatically confined to the well's interior. Thus there are no electrons near the exterior surfaces of the habitat. This feature enormously simplifies construction, operations, and even theoretical analysis (e.g., the electron plasma in this device is cylindrically symmetric instead of toroidal). In essence this device is a "bolt-on" shield, since any metallic structure in electrostatic contact with the electron well is protected – provided it stays well within the last magnetic flux line which passes through the electron well but does not touch the well's metal sides (any line that does touch is "shorted out").

The shield is energized by operating a 10 GeV Electron accelerator to shoot high energy electrons away from the habitat. Electrons form in the well when electrons from the solar plasma, attracted to the ever more positive habitat, are drawn along magnetic lines into the well. The main energy term in the system's energy budget is electrostatic energy, and this may exceed 10^{13} J of energy for a habitat sized like the Stanford torus (this energy is equal to 100 MW of power stored up over 1 day). This much energy could easily be transformed into penetrating radiations should a subsystem fail – for example, the magnetic cryogenic system. A safe procedure for dumping 10^{13} J of energy in a small fraction of a second is essential if the plasma core shield is to be usable.

One procedure is to accelerate positive ions away from the habitat. The electron cloud charge of 10^3 C is only about 10 mmol of particles, thus 1 percent of a mole of hydrogen ionized outside the metal structure would be enough to neutralize the habitat once the habitat's electric field had accelerated the ions away. In effect, the "charge" account is balanced by absorbing the electrons contributed by the ions – now receding from the habitat at great speed. Of course the electrons in the well are affected by this rearrangement. As the well's fringing electric fields die away the well electrons repel themselves along the lines of magnetic flux –

arranged not to touch the space habitat. Thus, in perhaps a millisecond, 10^{13} J and 10^3 C of electrons are safely neutralized. Obviously some more work should be done to verify this possibility.

Because a practical shield must remain in operation essentially 100 percent of the time, it must be possible to gain entrance or exit from the habitat at will – without turning off the shield. Since there are essentially no electrons external to the well this is not a difficult feat. It is only necessary to achieve varying levels of charge on objects being transferred from the habitat to the unshielded zone and back again. A device called a "shuttle shell" does this quite easily.

The shuttle shell is a Faraday cage equipped with electron/ion guns and a thruster unit. As the shuttle shell nears the habitat its electron gun bleeds off enough electrons (which go into the well) to equalize the potential between its cargo and the habitat. In reversing the operation the shuttle shell emits positive ions (which head for infinity) to neutralize its cargo. A subtlety of the shuttle shell's operation arises from the fact that like charges repel. Thus, a highly positive shuttle shell approaching a highly positive habitat feels a stiff "electric wind." To avoid excessive thrust requirements two shuttle shells might be used connected on either side of the docking port by cables which are winched in to draw the two shells to the dock, rather like cable cars.

Because the essential dynamic component of the plasma core shield is an electron plasma, plasma instabilities are to be expected. Experiments have shown that these can probably be controlled by varying the electron density as a function of radius. The real source of likely problems is the detailed systems engineering necessary to wed this device to a functioning habitat. Until extensive work is done to study all these ramifications the plasma core shield cannot be claimed as a practical solution to the radiation problem in space.

APPENDIX E

STRUCTURES BY VACUUM VAPOR FABRICATION

In making structures by vacuum vapor fabrication the goal is to create a uniform deposit of metal alloy with good mechanical properties. This should be accomplished with minimal equipment, labor, metal consumption, and environmental degradation. While a number of critical experiments must be performed, presently available information suggests that these goals may be attainable.

In physical vapor deposition of metals, most alloy systems show a fall density, fine grained microstructure at a substrate temperature 0.3 times the melting point of the metal (ref. 32). As substrate temperature is increased, the grains become coarser, the yield strength decreases, and ductility increases. Because these properties correspond to those of rolled and annealed sheet, vapor deposited metals have been termed "a true engineering material" (ref. 33). Despite the fairly consistent behavior shown by many metals, experiments must be performed with the specific alloys that are of structural interest for space applications.

Given a metal deposit of adequate yield strength and ductility, uniformity becomes of concern. Irregularities in the substrate are replicated in the final metal surface; the problem is to ensure that non-uniform metal buildup (across steps and grooves, for instance) leaves metal with structural strength in the zone underlying the irregularity. This is aided by increased substratic temperature (to encourage migration of surface atoms), by a nearly perpendicular atomic flux (to discharge self-shadowing), and by use of an initially smooth substrate. Adequate uniformity seems possible with the above controls; if needed, however, there are several promising means of eliminating defects part way through metal buildup.

The equipment used in vacuum vapor fabrication can be very lightweight. It handles sunlight, thermal radiation, rarefied vapor, and an aluminum feed rod; forces on it are virtually nonexistent. The greatest mass in the system appears to be the solar furnace mirror area, which is directly proportional to energy consumption. This consumption is, in turn, driven by the efficiency of energy use (thermal radiation to heat of vaporization), efficiency of vapor use (aluminum vaporized to aluminum reaching substrate), and by the total quantity of aluminum deposited.

Ignoring efficiency factors, for a heat of vaporization of 1.1×10^4 J/g, a colony mass of 300 kt, a solar constant of 1.4 kW/m^2, and a fabrication time of 1 yr, the ideal mirror area is 7.4×10^4 m^2. An average flux deviation from perpendicular of 20° probably represents adequate collimation; with proper evaporator design the inefficiency of vapor use should be less than 2.5 (unused vapor is condensed and recycled); even a poor energy efficiency should keep the total inefficiency below a factor of 10. Allowing a full factor of 10, the mirror area is 7.4×10^5 m^2. At 100 g/m^2, this is 0.74 kt.

The remainder of the system includes refractory metal foil boxes for the actual solar furnace evaporation units, plastic film hoods to intercept scattered metal atoms, and a carefully made balloon in the shape of the desired structure. Including these masses, the total system is very likely less than 1.5 kt; if the fabrication time were extended over several years this mass would be less.

Because colony structures have rotational symmetry, the solar furnace evaporation units can cover different areas as the colony rotates beneath their beams. With proper arrangement, complex shapes and structures can be created, and the direct human labor required for fabrication is very small.

APPENDIX F

INTERIOR BUILDING MATERIALS AND COMPONENTS

Building materials and components must be developed for use inside the colony compatible with the selected modular framing system. The need is for light and strong floor deck elements, light and fireproof interior wall elements, light, fireproof, and acoustically treated exterior wall elements, and fireproof ceiling assemblies. All of these elements must be selected on the basis of their specific functional use, concern for safety against fire, smoke and human panic, and appropriateness to their relationship within the overall design context of the interior environment of the colony. The elements have been designed assuming the availability of sufficient amounts of aluminum that meets the necessary strength requirements of NASA report MSC-01-542.[2] Also assumed available is a silicon-based fiberboard similar to terrestrial mineral fiber insulation board. The systems chosen are shown in table 4-8.

For floor and roof systems the lightest constructions generally available on Earth are composed of light, open-web framing, suspended ceilings, and metal floor decking. This is chosen for the baseline. Stressed skin panel construction made from aluminum web members and aluminum skin is also light and therefore a viable alternative. For a 9 m span and residential live loads (unreduced) of 1.9–2.9 kPa (40–60 lb/ft^2), the dead loads for each of these systems are given in figures 4-21 and 4-22.

TABLE 4-8.– WALL CONSTRUCTIONS

Exterior wall system
Cellular silicone glass (10 cm) with 22 ga aluminum skin on each side, 191 Pa (4 lb/ft^2)
or
2.5 cm aluminum honeycomb with 5 cm silicone foam glass and 22 ga aluminum skin on one side, 164 Pa (3.5 lb/ft^2)
Interior wall system
5 cm aluminum honeycomb with 22 ga aluminum skin on both sides, 120 Pa (2.5 lb/ft^2)

[2]NASA general working paper MSC-01-542 *A Preliminary Structural Analysis of Space-Base Living Quarters Modules to Verify a Weight Estimating Technique,* p. 45.

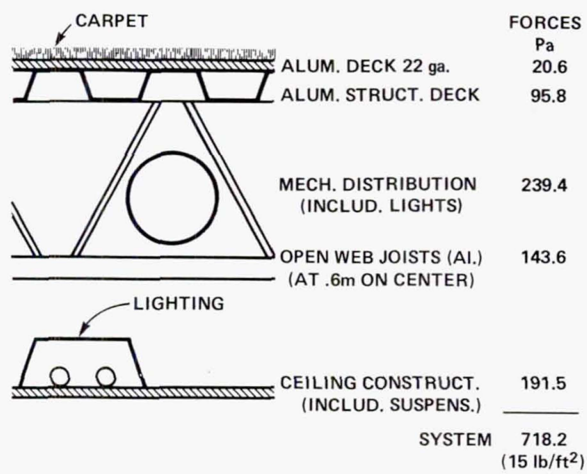

Figure 4-21.– *Alternative floor system – "stress skin."*

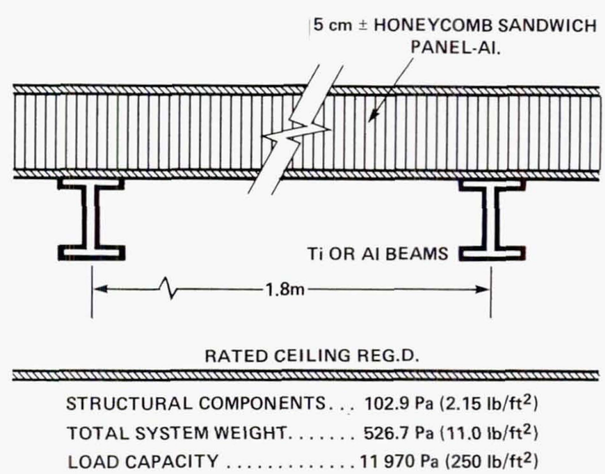

Figure 4-22.– *Baseline floor system.*

APPENDIX G

POPULATION DISTRIBUTIONS AND TRENDS

The U.S. population as described in the 1970 Census is used as a basis from which the colony properties are derived. The sex ratio is increased by about 10 percent in favor of the males and it is assumed that there is a substantial shifting of the population out of the more dependent ages – from under 20 and over 45 – into the 21-44 age class. Other assumptions include an increase in the participation of married women in the labor force and some fairly serious adjustments in the marital status distribution, all of which are directed toward increasing the proportion of the population in the effective work-force. These data are shown, with some comparable statistics for the United States, in tables 4-9 to 4-13.

From the numbers in table 4-14, it is apparent that systematic differences as to the proportions of the labor force engaged in production for export exist among U.S. communities of varying size. At a minimum, the percentage of workers engaged in work pertaining to the internal functioning of the community is approximately 30 percent, leaving 70 percent for export industry and for those who, by industrial standards, are not considered productive. These approximations are modified slightly to reflect features of early settlement, including a somewhat higher proportion of workers in internal activities. Table 4-15 shows the population development and the percentages of workers engaged in export activities for the first 14 yr following the beginning of construction.

TABLE 4-9.– AGE DISTRIBUTION

Age	U.S.-1970, percent	Initial colony distribution, percent	Colony U.S.-1970 differences, percent
0-20 yr	39.6	10.5	-29.1
21-44 yr	31.0	74.5	+43.5
45 yr & over	29.4	15.0	-14.4

TABLE 4-10.– SEX RATIOS
(Males per 100 females)

Age	U.S.-1970	Initial colony ratios
15-24	98.1	107.9
25-44	95.5	105.1
45-64	91.6	100.8

TABLE 4-11.– PERCENT EVER-MARRIED BY SEX AND AGE

Sex	Age								
	18-19	20-24	25-29	30-34	35-44	45-54	55-64	65-74	75 & over
U.S.-1970									
Male	8.1	43.1	80.7	87.6	91.8	94.5	94.9	94.2	95.1
Female	23.0	63.6	87.6	93.3	95.5	95.8	94.5	93.3	93.5
	18-20		21-44			45 and over			
Initial colony									
Male	10.1		75.0			94.0			
Female	30.0		80.0			94.0			

TABLE 4-12.– LABOR FORCE PARTICIPATION RATES BY AGE AND MARITAL STATUS – U.S.-1970 AND INITIAL COLONY ASSUMPTIONS

Sex and age	Single		Ever-married		
			U.S.-1970		
	U.S.-1970	Initial colony	Married spouse present	Other ever-married	Initial colony
Male					
16-19	54.6	---	92.3	68.8	---
18-20	---	98	---	---	92
20-24	73.8	98	94.7	90.4	98
25-44	87.4		98.0	92.3	
45-64	75.7	91	91.2	78.5	91
65 and over	25.2		29.9	18.3	
Female					
16-19	44.7	---	37.8	48.6	---
18-20	---	55	---	---	48
20-24	73.0	87	47.9	60.3	56
25-44	80.5		42.7	67.2	
45-64	73.0	80	44.0	61.9	54
65 and over	19.7		7.3	10.0	

TABLE 4-13.– POPULATION DISTRIBUTION BY AGE, SEX, AND MARITAL STATUS – INITIAL COLONY SETTLEMENT

	Total, both sexes	Male			Female		
		Total	Single	Ever-married	Total	Single	Ever-married
Total	10,350	5305	1600	3705	5045	1283	3762
Under 21 yr	1,081	567	557	10	514	483	31
Under 18 yr	864	452	452	---	412	412	---
18 to 20 yr	217	115	105	10	102	71	31
21 to 44 yr	7,713	3960	995	2965	3753	752	3001
45 yr and over	1,556	778	48	730	778	48	730

TABLE 4-14.– MINIMUM PERCENTAGES EMPLOYED IN 14 INDUSTRY CLASSIFICATIONS IN AMERICAN COMMUNITIES OF VARYING SIZE, 1960 AND 1950

Sector	Metropolitan areas 100,000-150,000		Cities of 10,000-12,500	
	1960	1950	1960	1950
Agriculture	0.9	1.1	0.1	0.4
Mining	.0	.0	.0	.0
Construction	3.5	3.8	2.7	2.5
Dur. mfg.	1.5	2.0	.5	1.2
Non-dur. mfg.	3.4	4.2	1.0	1.0
Transport	3.3	3.2	2.5	3.4
Wholesale	1.7	1.4	.6	1.1
Retail	12.3	12.1	10.5	11.9
Finance	2.2	1.8	1.4	1.6
Bus. serv.	1.6	1.6	.6	1.2
Pers. serv.	2.5	3.3	2.3	2.8
Entertaining	.4	.6	.2	.3
Professional	8.0	5.8	6.0	4.1
Publ. admin.	2.2	2.2	1.6	1.7
Total	43.5	43.1	30.0	33.2

Source: E. L. Ullman (1971) *The Economic Base of Cities.* Seattle: University of Washington Press.

TABLE 4-15.– POPULATION AND LABOR FORCE DEVELOPMENT – THROUGH THE 14TH YEAR FROM THE BEGINNING OF COLONY CONSTRUCTION AT L_5

Year	Total population	Total labor force[a]	Labor force engaged in "export activity"[a]
-3	200	200	
-2			
-1			
X[b]			
1			
2	600	600	
3	600	600	
4	2270	2270	
5			
6			
7			
8	2620	2620	
9	2620	2620	
10	2620	2620	
11	4350	3162	1932
12	6350	4616	2820
13	8350	6070	3709
14	10,350	7523	4597

[a]Labor force participation rates would be expected to decline to approximately U.S. levels eventually. Export activity as a proportion of total labor force assumed to resemble those found in U.S. communities of comparable size (after E. Ullman and others, 1971, *The Economic Base of Cities,* Seattle: University of Washington Press.

[b]X denotes the year in which colony construction begins.

APPENDIX H

SATELLITE SOLAR POWER STATIONS (SSPS)

A geosynchronous orbit is on the Earth's equatorial plane with a radius at which a satellite matches the Earth's angular velocity, and is stationary with respect to an observer on the Earth's surface. This orbit lends itself to communications, monitoring of the Earth's surface, and power transmission to the Earth's surface, all of which need to be done more or less continuously without interruption of service.

The power transmission concepts call for the collection of solar power by huge satellites, conversion to electrical power by either photovoltaic (ref. 34) or thermal methods (ref. 35) and transmission to the Earth by 10 cm microwave power beams (ref. 36). On the Earth's surface the power is to be received, rectified and then fed into the power grid.

The photovoltaic conversion satellite concept (see fig. 4-23) (under study by a group of companies headed by Arthur D. Little, Inc.) takes the incoming sunlight, which has an energy flux of almost 1.4 kW/m^2, concentrates it by a factor of 2 onto thin silicon solar cells,

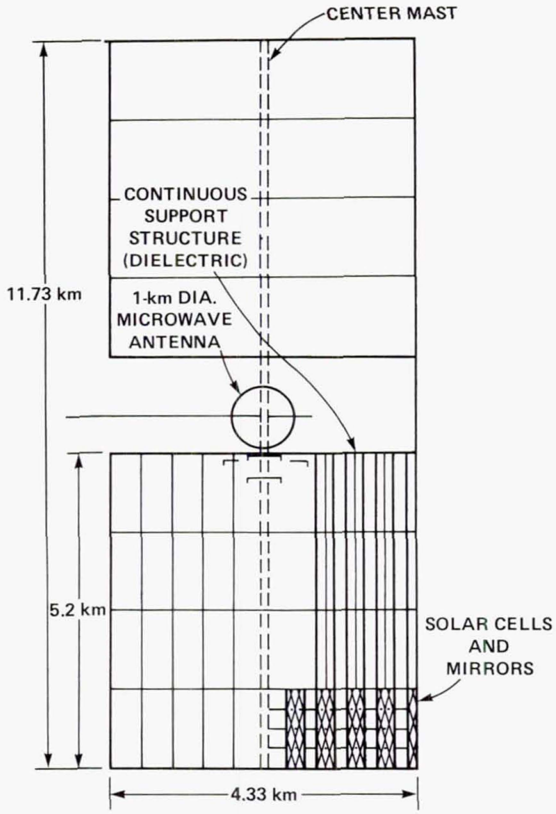

Figure 4-23.– *Photovoltaic SSPS.*

and beams 8 GW of power to Earth with an assumed dc to dc efficiency of 65 percent resulting in a received power of 5 GW. Studies presently indicate a mass/power ratio of 3.6 kg/kW for this satellite (ref. 37).

In the thermal conversion concept (under study by Boeing) 10,000 individually-steered facets concentrate the sunlight by a factor of 2000 into a cavity (personal communication with Gordon Woodcock, Boeing). In the cavity the sunlight heats helium which, in turn, drives Brayton cycle turbogenerators. The low end of the cycle is a large radiator operating at 550 K. (The model for the cycle and turbogenerators is a 50 MW plant in Oberhausen, Germany which uses a closed cycle with helium as a working fluid.) Four independent sections, each with 1 cavity, make up this SSPS. The power transmission is the same as for the photovoltaic SSPS. Studies indicate a specific mass of 6.5 kg/kW for 10 GW output received on Earth (ref. 35).

A solar power satellite built at the colony is transferred to geosynchronous orbit, requiring several months to complete the journey. Once in place the 5-20 GW system's output is tied into the terrestrial surface power grid to provide relatively cheap electricity to Earth.

A photovoltaic SSPS is expected to require little maintenance. Periodically, to overcome radiation damage, the solar cell arrays have to be annealed by heating them perhaps 50° C above ambient operating temperature; this is done automatically by the satellite. Failure of such parts as amplitron tubes and solar blankets, and the inevitable but infrequent hits by small meteoroids require repairs. A "smart" machine replaces parts on the transmitting antenna and the solar cell blankets, but repair of structural damage requires several people to help the "smart" machines.

It is desirable to do as little maintenance of solar power satellites as possible with people because the structure is not designed to provide life support for them. Also, the huge size of the satellite makes the amount of work one person can do negligible compared to a machine. For maintenance of a 5-20 GW photovoltaic power satellite a crew of less than 6 people is projected. For a thermal conversion power satellite more people are needed since there are more moving parts, but a crew of less than 50 is enough for a 10 GW satellite. The repair crew is housed in a small shack or "caboose" near the center of the satellite and rotated periodically to the habitat.

Because the satellite is a cheap stable orbital platform in sight of Earth all the time it also has on it packages of Earth-sensing instruments, direct broadcast TV stations, and communications links. Most of this equipment is located near the "caboose," so that the maintenance crew can take care of these units as well.

The major force on an SSPS is the gravity gradient torque. The amount of propellant required for station keeping depends upon the satellite's mass distribution and upon the station-keeping strategy adopted.

APPENDIX I

PROCESSING OF METALS

Methods for Refining Titanium

Figure 4-24 demonstrates various means for obtaining titanium from lunar ore. It is reasonable to expect that ilmenite could be obtained from lunar ore since a similar process on terrestrial ore is carried out commercially using a combination of magnetic, electrostatic and flotation separators. This requires crushing, gravity and a flocculant which lead to complicated but not insurmountable problems common to any wet-chemistry process. A further complication may be the presence of magnetic glass formed during meteoroid impacts. At the

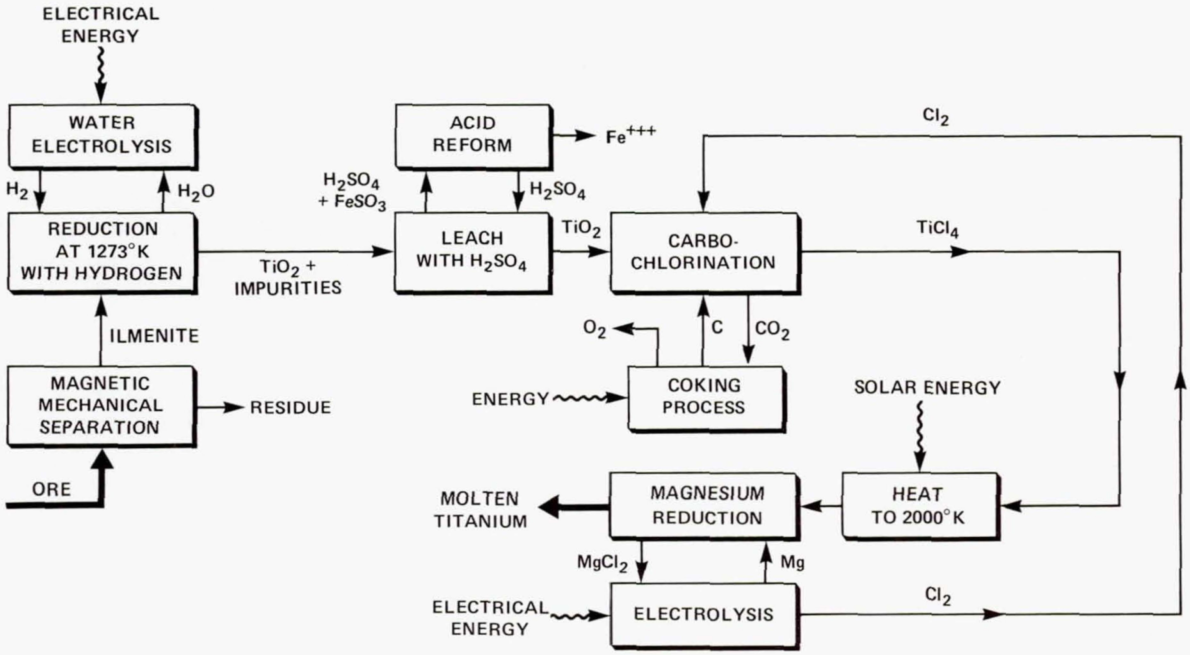

Figure 4-24.– *Titanium processing.*

next processing step the use of high temperature reduction of the ilmenite using hydrogen seems preferable.

The alternatives all require the consumption of carbon. On Earth this simply means the expenditure of coke, but in extraterrestrial processing it means that carbon must be recovered from carbon dioxide produced during the reduction or chlorination, which would have to be accomplished by high temperature reduction of the carbon dioxide with hydrogen. Obviously, it would save processing steps and mass if this process is applied directly to the ilmenite. The next processing step shown in figure 4-24 is the reduction of titanium dioxide. The appropriate method appears to be carbochlorination followed by reduction with magnesium to produce molten titanium. Important considerations are that magnesium is present in lunar ore and the production of titanium in liquid form makes continuous automated processing and alloying simpler to achieve.

Methods for Aluminum Extraction

The aluminum in lunar ore is in the form of plagioclase, $(Ca,Na)(Al,Si)_4 O_8$, while magnesium and iron remaining after ilmenite removal are in the form of pyroxene, $(Ca,Fe,Mg)_2 Si_2 O_6$. These are not normal sources of aluminum, magnesium and iron on the Earth because of the difficulty of economically separating the desired materials from association with such a wide variety of other elements. Literature was surveyed, and researchers at Bureau of Mines consulted to discover by what means metals or their oxides could be extracted from low grade ores comparable to lunar soil. Only two processes were found. These can be used to obtain alumina from anorthosite.

Anorthosite is a rock composed of plagioclase feldspar with minor amounts of pyroxene and olivine and is similar to the material found on the lunar surface. Figure 4-25 shows these processes. The method of soda-lime-sinter was eliminated because it consumes lime at a rate six times greater than it produces alumina, thereby requiring a disproportionate increase in plant size. The direct production of metals by electrolysis of molten anorthosite is often proposed, but the results of research have been discouraging. The remaining possibility is the melt-quench-leach process which in extensive laboratory tests has succeeded in recovering over 95 percent of the alumina present in the ore. In this process the ore is melted and then quenched to a glass. It is then treated with sulfuric acid to leach out the alumina component.

Further treatment of the aluminum sulfate follows standard procedures that have been developed for low-grade bauxites and clays. Figure 4-25 indicates that three paths are possible once alumina has been obtained. The Hall Process is unsuitable because it would be extremely difficult to automate, and it consumes its electrodes and electrolyte. The subchloride process is very attractive because of its simplicity. It consists of reacting aluminum chloride with alumina at high temperature to produce aluminum subchloride which later breaks down into aluminum and aluminum chloride. It has not been chosen as the baseline process because a pilot plant at Arvida, Quebec, was shut down when the process reportedly had difficulty on a large scale. The highly corrosive nature of the chloride vapor has been blamed for the failure.[3] Of the two remaining processes, carbochlorination followed by reduction with manganese (Toth Process) is a good possibility. However, it is a batch process yielding a granular product which must be removed, melted, and cast, and requires an extra carbon reduction process. The high temperature electrolysis method is continuous and yields liquid aluminum ready for casting into ingots. For these reasons it has been chosen. However, research should take place into the possibility of a melt-quench process (no leach) followed by direct extraction with a subchloride process which, in theory, could reduce the plant mass by approximately 1/2.

[3]Information about commercial aluminum ventures is extremely tentative and difficult to obtain because of proprietary interests.

APPENDIX J

GLASS PROCESSING

The chemical composition of lunar samples returned by the Apollo missions has been determined, and a wide variation of percentages by weight of various constituents is apparent (refs. 38,39).

Silica (SiO_2) composes approximately 40-50 percent of the lunar soil, and in abundance are also found oxides of aluminum (Al_2O_3), iron (FeO), magnesium (MgO), calcium (CaO), and titanium (TiO_2). Oxides of sodium (Na_2O), potassium (K_2O), phosphorus (P_2O_3), manganese (MnO), and chromium (Cr_2O_3) are present in less than 1 percent.

In the manufacture of window sheet and plate glass, soda-lime glass is most commonly used. Its composition includes approximately 71-73 percent silica (SiO_2), 12-14 percent soda (Na_2O) and 10-12 percent lime (CaO) (ref. 40). Soda is absent from the lunar soil in percentages needed for producing commercial soda-lime glass and it proves to be a costly item to supply from

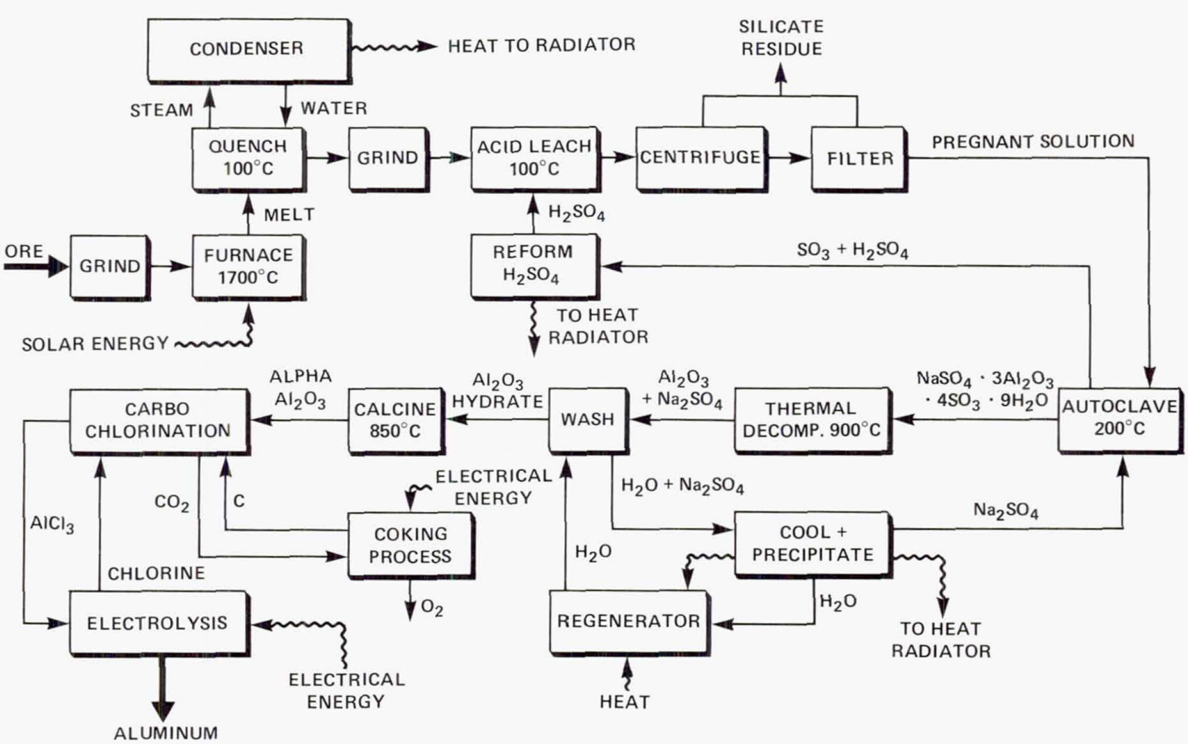

Figure 4-25.– *Aluminum processing.*

Earth.[4] Fortunately, it does not appear to be necessary to supply additional Na_2O. Commonly used oxides in commercial glass which, if desired, would by necessity be additives to be mixed with the lunar materials, include lead oxide (PbO), used to provide X-ray and gamma-ray protection by absorption (ref. 41) and boric oxide (B_2O_3), used when good chemical resistance, high dielectric strength, and low thermal expansion are desirable (ref. 42).

A simplified diagram of industrial glass-making is given in figure 4-26 with lunar soil listed as the raw material to be provided. After additives (if any) are mixed with the lunar soil, the acid leaching stage removes undesirable materials from the mixture, such as iron oxides which degrade the transmissivity of the glass. If it is decided to produce almost pure silica glass (> 95 percent SiO_2) almost all of the non-silicate constituents are leached out with acid at this stage. The furnace temperature needed to melt pure silica (~ 1700° C) is higher than that needed for soda-lime glass (~ 1550° C) but is well within the limits of the solar furnace to be utilized. Requirements for providing these temperatures are calculated as follows:

[4] Blumer, J., Libbey-Owens-Ford Company, Toledo, Ohio, personal communication, Aug. 1975.

Assumptions:

1. 40 t/day maximum production schedule
2. 24 hr work day
3. Mean specific heat (0°-1700° C) ~ 1.13 J/g °C for silica glass (ref. 43).
4. Mean specific heat (0°-1550°C) ~ 1.21 J/g °C for soda-lime glass (ref. 43).
5. Insolation, 1.39 kW/m².

For silica glass, ~ 890 kW (640 m² solar collector) is needed. For soda-lime glass, ~ 870 kW (626 m² solar collector) is needed.

Volume requirements for the processing plant are governed basically by the volume needed for the melting tank and the annealing lehr. Although most industrial processes for plate glass involve capacities substantially greater than 40 t/day, the following estimates based upon a scaling down from larger systems are given as guidelines: approximately 23 m in length for the tank, 91-122 m in length for the annealing lehr, 1-2 m in depth, and, to allow for trimming, a width of 0.3-0.4 m in excess of the desired width of the glass panels. Note that some processes have annealing lehrs of only 10 m in length (ref. 44). For panels 0.5 m in width, the volume of the tank and lehr assembly using the upper values of the above dimensions is about 280 m³. Additional space must be provided for the preliminary processing and cutting phases.

A rough estimate for the weight of a plant processing 40 t/day is 400 t.

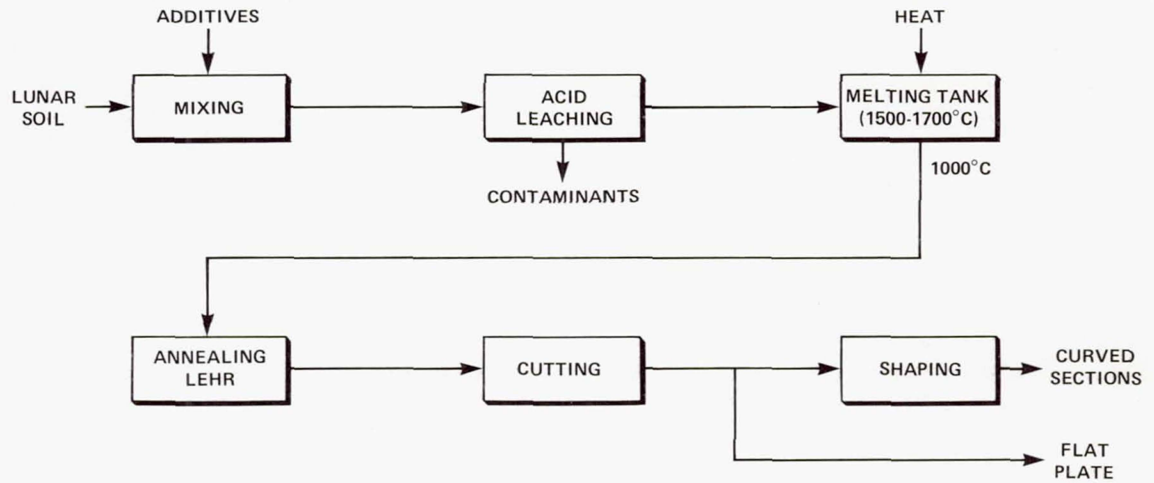

Figure 4-26.– *Glass processing.*

APPENDIX K

THE LUNAR GAS GUN MASS DRIVER

The importance of obtaining the mass of material from the Moon has been emphasized earlier. Overall probability of success of the entire system is substantially improved by having an alternative to the transport linear accelerator (TLA) and the mass catcher that has been selected as the primary or baseline system for transporting 10 million tonnes of lunar material to L_5 over a period of 10 yr.

The lunar gas gun is a fundamentally different concept to that of the TLA. Where the TLA launches small payloads with very high repetition rate onto a precisely determined trajectory, and has the small individual loads caught in a localized active net or passive catcher, the gas gun launches large payloads with a much lower repetition rate onto a less precisely determined trajectory and has these large payloads collected by remote controlled interceptor rocket engines.

The gas gun has four primary elements in its system: a) the launching barrel on the lunar surface, b) the energy storage system which uses compressed hydrogen to propel the payload, where the propulsion energy is obtained from the hydrogen gas maintained at a pressure of 200 MPa in a blast hole deep beneath the lunar surface, c) the compressor which maintains the gas at high pressure and is driven by a nuclear turbine, and d) the interceptor rockets.

Launching Barrel

The equations that govern the mass of the launching barrel are:

$$\sigma_W = \frac{PR}{t}$$

$$2\pi RPL = \frac{1}{2}mv^2$$

$$M = 2\pi RLtP$$

where

- σ_W is the working stress of the barrel material, Pa
- R radius of the barrel, m
- t thickness of the barrel, m
- P internal pressure (presumed constant), Pa
- L length of the accelerating region, m
- m mass of the projectile, kg
- v muzzle velocity, m/s
- M mass of the barrel, kg
- ρ density of the barrel material, kg/m^3

These equations together yield the following approximate expression for the barrel mass which depends *only* on the properties of the barrel material, the muzzle velocity, and the mass of the projectile:

$$M = (\rho/\sigma_W)v^2m$$

For hydrogen at 200° C, when the thermodynamic properties of motion near the speed of sound are taken into account, this expression becomes:

$$M = 5.22(\rho/\sigma_W)v^2m$$

For lunar escape velocity of 2370 m/s, and for a boron or graphite filament epoxy such as PRD-49 of density 1.38×10^3 kg/m^3 and an allowable working stress of 1650 MPa, the mass ratio of barrel to projectile is 24.5.

Projectile Mass

Given a desired mass flow rate of 10^6 t/yr the projectile mass varies inversely as the launch repetition rate for a single barrel. Since large payloads are desired at low repetition rates, the largest projectile that can be handled on the lunar surface represents the best solution to this element of the system taken alone. Since a 10-t shell is a reasonable size for a shell on the Earth's surface, a 57-t projectile is assumed to be manageable on the lunar surface. With this value the desired mass flow rate can be achieved with a repetition rate of 2 launches per hour. A cylindrical projectile of this mass sintered from lunar material and having a density presumed to be 2.5 can be about 2 m in diameter and 4 m long. The mass of the barrel for a projectile of this size is about 1400 t.

Gas Storage

The compressed gas can be stored in a deep sublunar hole which can have a diameter of approximately 30 m and can, if necessary, be lined with a heavyweight plastic film. The mass of the film is not expected to exceed 5 t.

Nuclear Compressor

The average power required to launch 1 million tonnes at lunar escape velocity over the course of a year is 89 MW. The energy for this comes from a nuclear turbine and gas compressor. For a nuclear electrical power generator the study assumes a mass-to-power ratio of 45 Mt/MW (exclusive of shielding). Although an electrical generator is inherently more efficient than a gas compressor, perhaps by a factor of 2, the compressor has a much lower ratio of mass to power throughput, a factor of from 5 to 10. The combined effect on the overall energy source is assumed to reduce the mass to power ratio to 27 Mt/MW. Thus the mass of the nuclear compressor may be taken as approximately 2400 t.

Remote Controlled Interceptor Rockets

The large blocks of lunar material arrive in the vicinity of L_5 at an average rate of one every 1/2 hr. With an anticipated launch velocity error of ±0.5 m/s, the radius of the scatter circle is approximately 1000 km. If 50 interceptor rockets are used to collect the lunar material the rotation time to intercept and dock is 24 hr. If this maneuver is carried out with as small velocity change as possible, the average power required to collect the lunar material is 1.2 kW, or 37.8 J/kg of material.

A more accurate study of this part of the problem is desirable. Perhaps the interceptors could rendezvous and correct the trajectory at a point closer to the Moon. It might also be possible to schedule the timing of launches and the direction of trajectories to take advantage of the relative velocities of the Moon and the L_5 processing location which is in a large orbit around the L_5 point.

Lunar Gas Gun Summary

Many aspects of this system need to be studied further. For example, the thermodynamic efficiency should be determined with greater accuracy. It is now merely assumed to be nearly 1 percent because the temperature of the gas never differs from the ambient temperature by more than about 20° C and then only for a short time. The process is, therefore, considered to be a quasi-isentropic, adiabatic, expansion/compression. No losses at the valves are taken into account. The valves can be seen in the schematic of the launcher, figure 4-27, which indicates that the launching gas is not allowed to escape. Some indication is also given in the figure that fine velocity control might be developed to reduce the scatter circle at L_5.

For comparative purposes, the component masses of the lunar gas gun are compared in table 4-16 with the corresponding masses of the transport linear accelerator.

TABLE 4-16.– COMPARISON OF THE MASSES OF THOSE PARTS OF THE TLA AND THE LGG MASS DRIVING SYSTEMS THAT MUST BE LOCATED ON THE LUNAR SURFACE (IN TONNES)

	Lunar gas gun (LGG)	Transport linear accelerator (TLA)
Driver	1400	4000
Power source	2400	9000
Total	3800	13,000

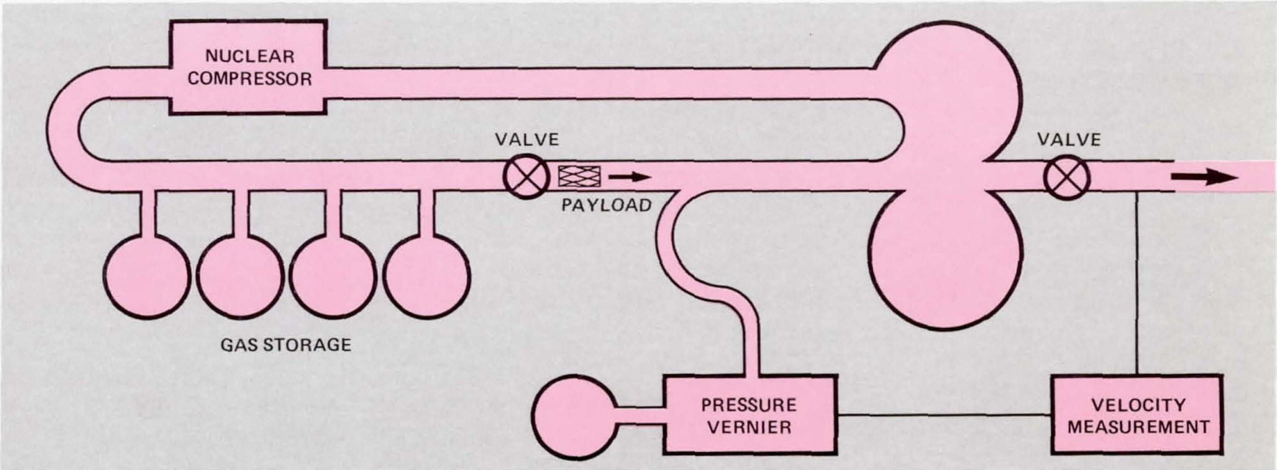

Figure 4-27.– *Lunar gas gun.*

APPENDIX L

PASSIVE CATCHERS

Two different designs for passive catchers, although rejected for the baseline, were considered in some detail. Figure 4-28 illustrates one version of a passive catcher. It consists of two major parts: a slowly spinning bag of Kevlar fabric, and a non-spinning rim which contains power, propulsion and other necessary systems. (Such "dual-spin" designs are commonly used in satellites.) To keep the mass of the catcher within reasonable limits, it is limited to 100 m in radius. Consequently the dispersion of the incoming payloads must be less than this. After the incoming masses arrive within the 100 m radius of the target area, they strike a grid of cables across the mouth of the catcher and break up, thereby releasing a spray of fine particles and small gravel-size rocks which fly inward. These particles strike the bag at up to 200 m/s (23 ply Kevlar stops 44 magnum bullets fired point blank) and come to rest against the surface of the bag where they are held by centrifugal force thereby preventing them from drifting free and escaping from the mouth. Uncertainty about achieving the accuracy of launching required for this catcher, and also some doubt about whether the material would break up and be contained as planned, led to the rejection of this alternative.

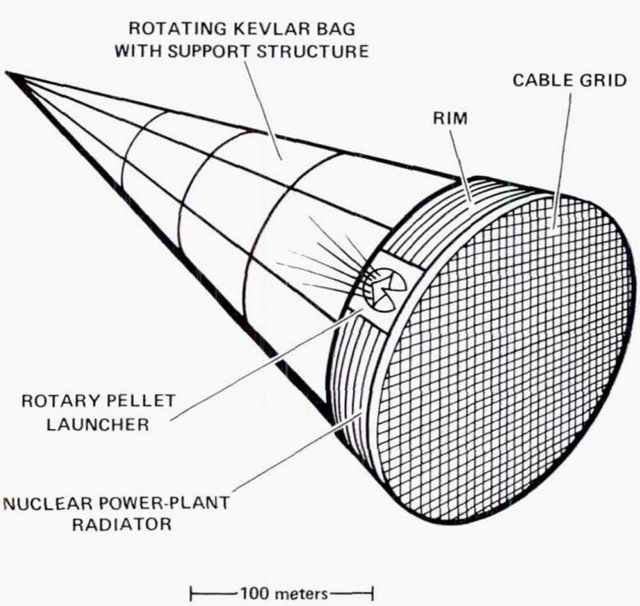

Figure 4-28.– *Passive bag-catcher concept.*

A second version of a passive catcher is a circular disk, 10,000 m^2 in area, of crushable material such as rigid foam or bonded, glass wool boards. A payload would penetrate this material dissipating its energy and lodging in the material from which it could be retrieved at a later time. Theoretical analysis shows that a typical payload would penetrate about 1.3 m into FR type polystyrene foam (density of 28.4 kg/m^3). The foam catcher could be foamed in place. After collecting for a period of time it could be melted down with a solar furnace; the desired material extracted; and the catcher refoamed in space. It has the advantage of being very simple in conception, but its 500 t of mass is a disadvantage, as is the fact that, at least initially, the plastics for making the catcher would have to come from Earth. Eventually it would be possible to use mostly lunar materials such as bonded glass wool. Like the other passive catcher, the foam catcher requires very high precision in the launchings.

APPENDIX M

SPACE TRANSPORTATION SYSTEMS

Earth Surface to Low Orbit

Figure 4-14 gives specifics of lift vehicles proposed for transport to 500-km orbit. They are: a) the standard Space Shuttle; b) its two solid rocket booster (SRB) heavy-lift-vehicle (HLLV) derivative, obtained by replacing the Shuttle Orbiter with a payload fairing and by packaging the three Space Shuttle main engines (SSME) in a recoverable ballistic-entry body, and c) the four SRB Shuttle derivative, with four SSMEs.

Transport Beyond Low Earth Orbit

The nominal mission is the round-trip from low Earth Orbit (LEO) to L_5, with Δv of 4084 m/s for a one-way transfer. The NERVA nuclear rocket gives a specific impulse (I_{sp}) of 825 s, or, with operational cooldown losses, 800 s. The SSME has I_{sp} of 460 s. But with a 6:1 mixture ratio and extraterrestrial oxygen resupply available at L_5, the effective I_{sp} for the nominal mission is raised to 721 s. Consequently the SSME was selected. Its characteristics are as follows:

Thrust – 2.09 MN
Emergency power – 109 percent
Chamber pressure – 20.4 MPa
Area ratio – 77.5 (1975)

Specific impulse – 460 s
Mixture ratio – 6.0:1
Length – 4.24 m
Diameter – 2.67 m × 2.41 m, powerhead
2.39 m nozzle exit
Life – 7.5 hr; 100 starts
Weight – 2869 kg

Electric-propulsion technology rests upon use of the 30-cm Kaufman thruster and its derivatives. Nominal characteristics when used with mercury propellant are as follows:

Thrust – 0.14 N
Specific impulse – 3000 s
Input power – 2668 W
Power efficiency - 79.3 percent
Propellant utilization efficiency – 92.2 percent
Beam current – 2 A
Beam potential – 1058 V

Because mercury cannot be obtained from the Moon, it would be advantageous to use another propellant. For use with propellants other than mercury, there is the relation, 1/2 (thrust) × (exhaust vel.) = (power), and exhaust velocity scales as $1/\sqrt{(\text{molecular weight})}$. Ionization potentials as high as 15 eV are admissible, when operating with propellants other than mercury. Gaseous propellants are of interest because they obviate the need for heating the thrust chamber to prevent condensation of propellant. The 30-cm thruster has been run at high efficiency with xenon, krypton, and argon. Use of oxygen is of interest because of its ready availability and moderate ionization potential (13.6 eV) and molecular weight (32). Its use would require the cathode and neutralizer element to be of platinum to resist oxidation. It would be preferable to use large numbers of such thrusters rather than to develop very large single thrusters; a 10,000-t vehicle accelerated at 10^{-5} g would require 6000 mercury thrusters or 20,000 oxygen thrusters.

Table 4-17 gives the following estimating factors for use in space transport where appropriate:

1. Transfer Δv, following recommendations from NASA
2. Mass-ratio for H_2/O_2, I_{sp} = 460 s
3. Mass-ratio for H_2/O_2 with O_2 resupply available either at L_5 or at the lunar surface; mixture ratio, 6:1
4. Mass-ratio for ion propulsion, I_{sp} = 3000 s

For a multi-leg mission, the total Δv is the sum of the individual Δv's and the total mass ratio is the product of the individual mass ratios. Mass ratio is found from

$$\Delta v = g_o I_{sp} \ln \mu$$

where g_o = acceleration of gravity = 9.81 m/s^2, μ = mass-ratio.

The following mass factors express the ratio, (initial mass in LEO)/(payload delivered to destination). Rocket engine uses LH_2/LO_2 at 6:1 mixture ratio; structural mass fraction is 0.1; I_{sp} = 460 s.

I. Round trip, LEO-L_5, vehicle returned to LEO
   a. No resupply, all propellants carried to LEO: 4.0
   b. Resupply at L_5 for down trip only: 2.83
   c. Resupply at L_5 for both legs of trip: 1.97
II. Delivery to the Moon
   a. One-way flight with single-SSME modular vehicle: 5.06
   b. Chemical tug LEO-L_5-LPO-L_5-LEO, with NASA-recommended lunar landing vehicle based in parking orbit; only LH_2 from Earth, all O_2 at L_5: 3.34 (LPO refers to lunar parking orbit).
   c. One-way trip; L_5 oxygen used to maximum extent: 3.08

Specifications for a single-SSME modular vehicle assembled in LEO are:

Initial mass in LEO: 4.16×10^6 kg
Propellant (LH_2/LO_2, 1:6 mixture ratio): 3.03×10^6 kg
Structural mass: 0.31×10^6 kg
Engine and avionics: 9.1×10^3 kg
Payload: 0.82×10^6 kg
Mass delivered to Moon: 0.87×10^6 kg
Thrust/weight at landing: 1.16
Estimating factor: 5.06

These characteristics assume a two-stage operational mode, with empty tankage staged off (jettisoned) upon reaching lunar parking orbit (LPO), prior to final descent. The propellant and tankage masses are as follows:

LEO-LPO: Propellant, 2.49×10^6; structure, 0.25×10^6 kg
LPO-LS: Propellant, 0.56×10^6; structure, 0.055×10^6 kg
(LS = lunar surface)

The vehicle requires a multi-burn injection mode to reach Earth escape velocity. This offers the possibility of further mass savings since expended tankage can be staged off after each burn. This factor is not considered here.

There is much discussion of reusable lunar transporters. But where propellant must be brought from Earth, the tankage of such a transporter cannot be refilled. The reason is that cryopropellants must be brought to orbit in their own tankage, and zero-g propellant transfer offers no advantages.

The transporter carries 6 standard payload modules, 136,900 kg each, in a hexagonal group surrounding a central core module. This carries engine and propellant for a lunar landing. Hence, the vehicle which lands on the Moon is of dimensions, 25.2 m diam X 30 m long. Additional propellant for Earth escape is carried in modules forward of the payload; four 8.41 m diam X 30 m long modules are required. Total vehicle length in LEO is 60 m.

APPENDIX N

IMPACT OF EARTH LAUNCH VEHICLES ON THE OZONE LAYER

Hydrogen chloride gas (HCl) produced from the exhaust of the Space Shuttle booster motor (see fig. 4-29) dissociates to produce free chlorine which, in turn, reacts to remove ozone from the stratosphere by the following catalytic reactions:

$$Cl + O_3 \rightarrow ClO + O_2$$

$$ClO + O \rightarrow Cl + O_2$$

TABLE 4-17.– ESTIMATING FACTORS FOR SPACE TRANSPORT

From			To: Lunar parking orbit	To: Low Earth orbit	To: L_4/L_5	To: Geosynch. orbit	To: Lunar surface
From	Lunar parking orbit	(1)		4084	686	1737	2195
		(2)		2.47	1.16	1.47	1.63
		(3)		1.25	1.03	1.08	1.10
		(4)		1.20	1.03	1.08	---
	Low Earth orbit	(1)	4084		4084	3839	
		(2)	2.47		2.47	2.34	
		(3)	---		---	---	
		(4)	1.20		1.20	1.19	
	L_4/L_5	(1)	686	4084		1737	
		(2)	1.16	2.47		1.47	
		(3)	1.03	1.25		1.08	
		(4)	1.03	1.20		1.08	
	Geo-synch. orbit	(1)	1737	3839	1737		
		(2)	1.47	2.34	1.47		
		(3)	1.08	1.23	1.08		
		(4)	1.08	1.19	1.08		
	Lunar surface	(1)	1859				
		(2)	1.51				
		(3)	1.09				
		(4)					

NOTES:

(1) Gives Δv's for impulsive (Hohmann) transfers and may be less than Δv's for ion propulsion. A 30-percent increase in Δv has been assumed to account for this effect.

(2) Gives mass-ratio, μ, for H_2/O_2 assuming $I_{sp} = 460$ s.

(3) Gives mass-ratio, μ, assuming an extraterrestrial supply of oxygen.

(4) Gives mass-ratio, μ, for ion propulsion.

One-dimensional models of HCl deposition, vertical transport, and chemical production and removal of participating trace stratospheric constituents (OH, O, $O(^1D)$, O_3, CH_4, H_2, and NO) have been used by NASA to simulate ozone depletion (refs. 45,46). Steady-state solutions were obtained simulating 60 shuttle launches per year given that the emissions were spread uniformly in the horizontal over a hemisphere and over a 1000-km wide zone. The levels of ozone reduction computed were about 0.3 percent and 1.0 percent, respectively. More recently, Whitten has revised the ozone depletion calculation for the hemisphere downward to less than 0.1 percent (personal communication, July 1975). Launch rates that might be anticipated for the initial colonization program are shown in table 4-18.

The reduction in ozone concentration in the upper levels of the atmosphere allows the molecular oxygen dissociating radiation to penetrate lower before producing ozone; hence, a primary effect is a downward shift in the ozone distribution. A reduction in the total ozone concentration, which would appear to be very minor, results only as a secondary effect.

Advanced launch vehicles using liquid oxygen-liquid hydrogen ($LOX\text{-}LH_2$) propellants above 30 km would eliminate the emission of hydrogen chloride into the stratosphere; however, there are also potential problems with hydrogen fuel which produces water. Water is dissociated as:

$$O(^1D) + H_2O \rightarrow 2OH$$

in which the $O(^1D)$ results from ozone photolysis at wavelengths shorter than 310 nm. The OH reacts with odd oxygen in a catalytic cycle

$$OH + O_3 \rightarrow HO_2 + O_2$$

$$HO_2 + O \rightarrow OH + O_2$$

However, compared to the 2 ppm of water in the stratosphere, increases due to hydrogen combustion may be negligible. Further study of the problem is required (R. Whitten, NASA-Ames Research Center, personal communication, August 1975).

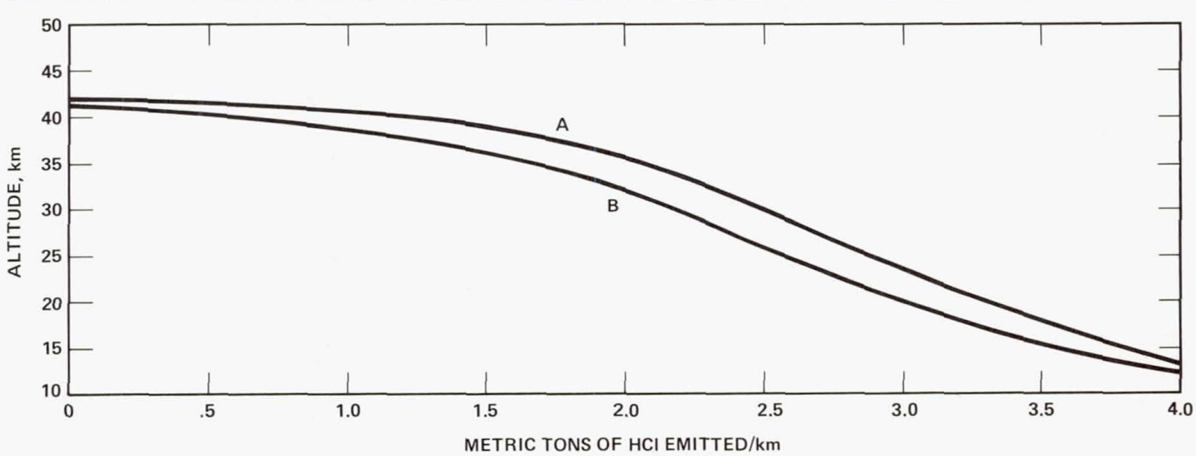

Figure 4-29.– *Altitude distribution of HCl deposition rate from a Space Shuttle launch vehicle (A-JPL, 1975, B-Oliver, 1973).*

TABLE 4-18.– ANTICIPATED LAUNCH RATES IN LAUNCHES PER YEAR[a]

Year from start of colonization program	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Max.	Total
HLLV (150 t/launch)	–	–	–	–	9	26	23	53	54	71	65	49	53	65	69	76	72	72	67	73	73	73	76	1043
Space Shuttle (30 people/launch)	–	–	–	–	13	13	13	20	17	27	27	100	100	100	83	83	83	83	80	80	80	80	100	1082
TOTAL	–	–	–	–	22	39	36	73	71	98	82	149	153	165	152	159	155	155	147	153	153	153	165	2125

[a]No provision for launching propellant is included in these numbers; its inclusion will more than double the annual launch requirements.

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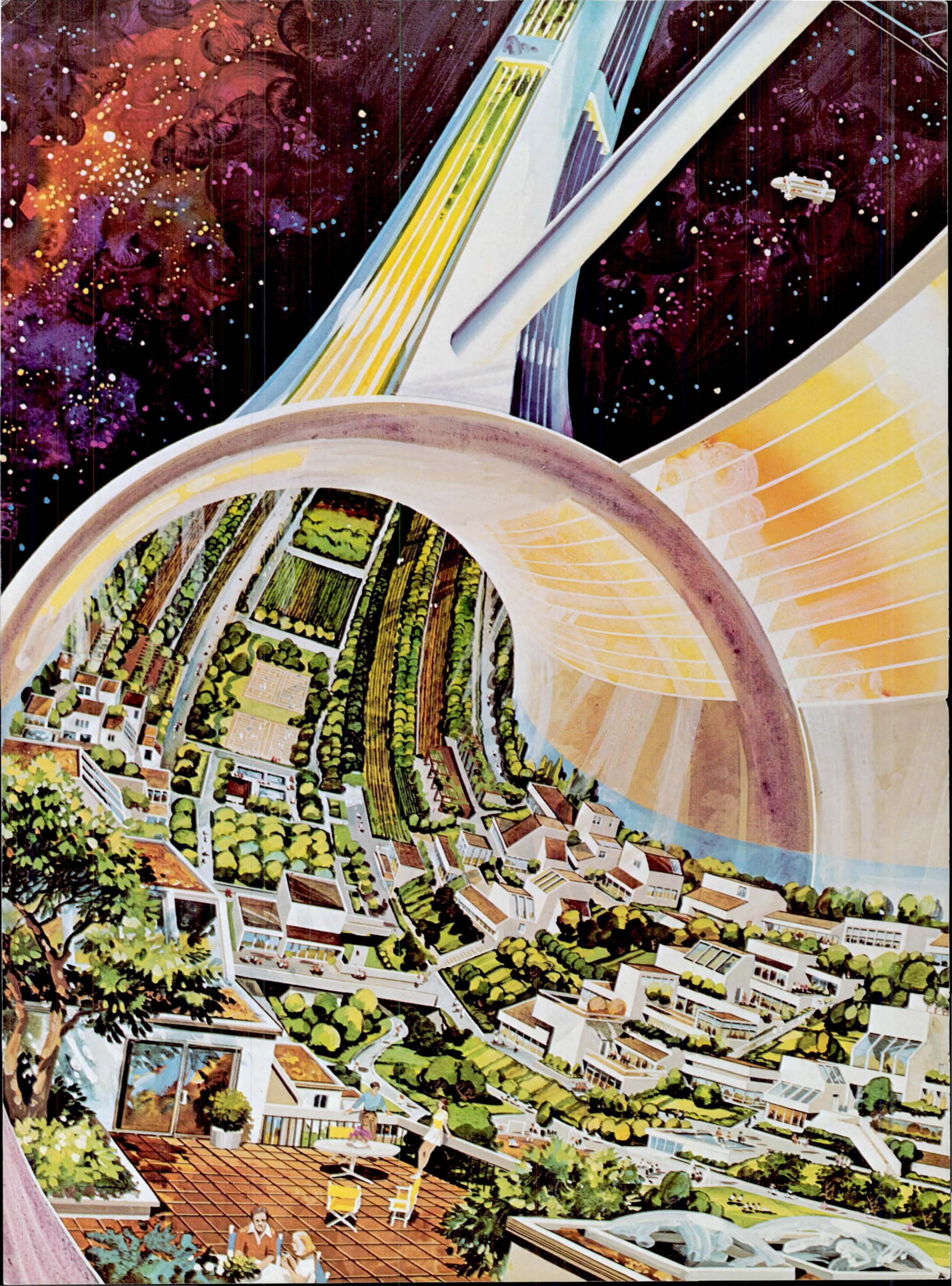


5. A Tour of the Colony

During the final stages of construction of the habitat, colonists begin immigrating to L_5. Within a few years a small but thriving human community is established. Its architecture, agriculture, commerce, culture, and even the individual people reflect a dedicated emphasis on productivity.

Imagine that you are a visitor on a tour of this colony. Your experiences during such a visit are shown in italics in this chapter to act as counterpoints to the continuing technical descriptions which conform with the arrangement of the other material in this report.

EARTH TO LOW EARTH ORBIT

Preparation for your trip is a difficult period; it eliminates those who are not serious about their intention of going to the space colony. You undergo weeks of quarantine, exhaustive physical examinations, stringent decontamination, and interminable tests to make sure that you do not carry insects, bacteria, fungi, or mental problems to L_5. Only then are you permitted to board a personnel module of a heavy-lift launch vehicle which everyone refers to as the HLLV, along with 99 prospective colonists who have gone through even more rigorous tests than you have as a mere visitor.

In the following hour events move at breakneck speed. Your vehicle is launched. Acceleration thrusts you into your contoured seat. Minutes later it ceases and you are in orbit 240 km above the Earth and having your first experience of being weightless. The orbit is a staging area at which an entire section of the HLLV, the personnel carrier containing you and the colonists, is transferred to an inter-orbital transport vehicle known as the IOTV. This is the workhorse transporter that moves people and cargoes between points in space, and never lands upon any planetary body. Its structure seems frail and delicate compared with the airplane-like structure of the HLLV.

During the construction phase of the colony, the staging area handled replacement supplies at the rate of 1000 t a year. The growth and increasing population loading of the colony required transshipment of an average of 50 people per week together with their personal belongings and the additional carbon, nitrogen, and hydrogen needed to sustain them in space. Oxygen, and other elements, are obtained from the Moon. Later the big demand was for lightweight, complex components fabricated for satellite solar power stations. Initially the resupply of the lunar base also came from Earth. The 150 people on the Moon require 250 t of supplies and rotation of 75 people to Earth each year. Furthermore, there is traffic from the colony to Earth. Studies of past colonizations on Earth have shown that discontent with frontier life is usually such that many colonists wish to return home.

Cargo was brought up on earlier flights of HLLV's so that you do not have to wait long in the staging orbit. T'is reduces the amount of consumables needed to support the people between Earth and the colony. Every effort is made to get you to the colony as quickly as possible once you have attained Earth orbit. The freight had been transferred to the IOTV before your arrival, so no time is lost in moving the personnel carrier from the HLLV to the IOTV. The rocket engines of the IOTV begin to thrust and the vehicle breaks from Earth orbit and begins its 5-day journey to L_5. You find that conditions within the personnel carrier are crowded somewhat like the transcontinental charter flights you experienced on Earth.

THE HABITAT AT L_5

Like countless other tourists over the years you look for the first view of your destination. Just as European immigrants looked for the concrete towers of New York and the torch-bearing statue, you now anxiously await your first glimpse of the wheel-like structure spinning amid the black backdrop of space. Only in the last day before your arrival is your search rewarded. And then you are surprised at how small the space colony looks. Since you cannot judge distance in space, the colony appears first as a mere point of light that gradually exceeds the other stars in brightness, and then it forms into a narrow band of sunlight reflected from the radiation shield. Later you

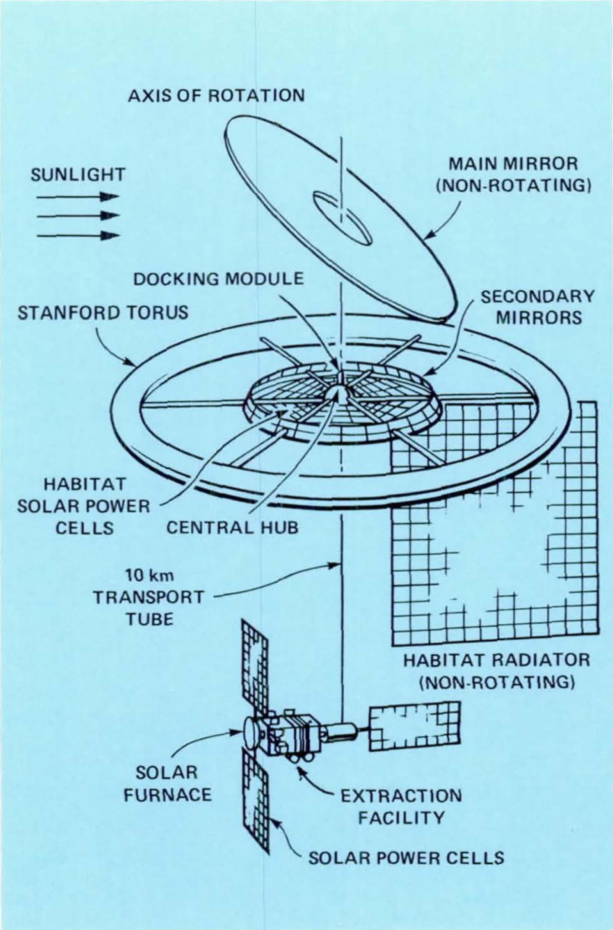


Figure 5-1.– *Colony configuration.*

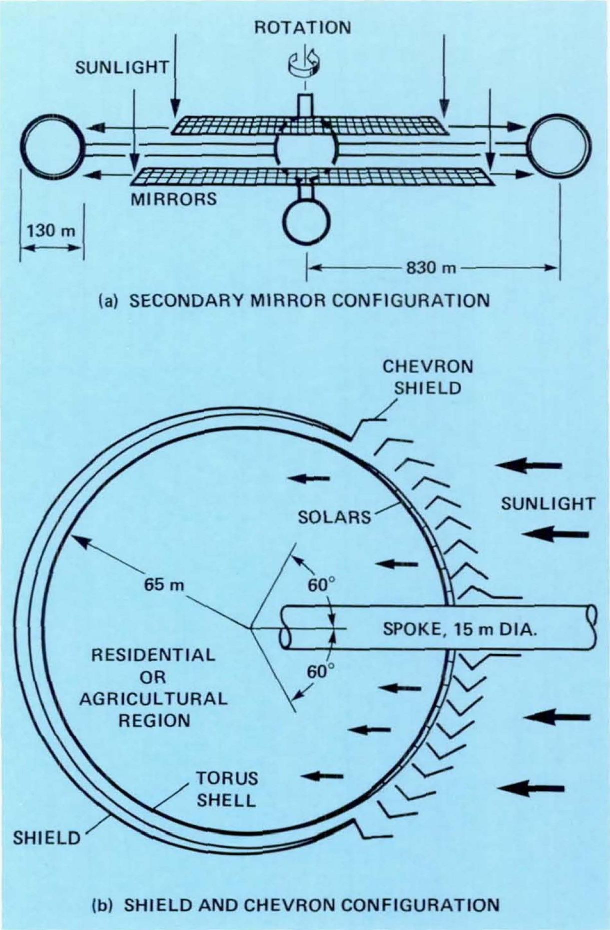


Figure 5-2.– *Cross section of the torus.*

see the spokes and the hub. But still the 10 million tonnes of slag and Moon dust that have been compacted and placed around the habitat like a bicycle tire, seem no larger than the rim of a balance wheel in a ladies' watch.

Only in the last few hours of the trip, when the IOTV has matched its orbit with that of the colony and is waiting to dock, do you see the true extent of the habitat and begin to comprehend the immense nature of this man-made structure in space.

The View From the Outside

The space colony appears as a giant wheel in space. Still you cannot comprehend its size, but you know it must be huge. One of the other passengers who has been on the trip before tells you it is 1800 m in diameter. He points to the six spokes connecting the wheel rim to its hub and tells you each is five times as wide across as is the cabin of your space transport. You look in awe. He tells you that the rough-looking outer "tire" is really a radiation shield built of rubble from the Moon. It protects the colony's inhabitants from cosmic rays.

In reply to your question about the burnished disc that hangs suspended above the wheel of the space colony, he explains that it is a big mirror reflecting sunlight to other mirrors which, in turn, direct the light rays through several other mirrors arranged in a chevron form to block cosmic rays.

As you watch you become aware that the spokes are rotating, but you cannot see any motion in the rim. Again your companion explains; the habitat rotates within the outer shield. Rotation is needed to simulate gravity, but rotating the massive shield would produce high stresses that would require a much stronger structure. The inner habitat tube is accurately positioned within the outer shield so that the two do not scrape against each other.

He points to the hub of the wheel and tells you that is where your transport is heading to dock with the space colony, explaining that local custom has named the docking area the North Pole.

Figure 5-1 presents a general perspective of the principal components of the habitat. The torus provides the space for housing, agriculture, community activities, and light industry within a 130-m-diam tube bent into a wheel approximately 1800 m in diameter. Six spokes, each 15 m in diameter, connect the torus to a central hub and accommodate elevators, power cables, and heat exchange pipes between the torus and the hub. The spokes also act as diametric crossties to resist excessive deformations of the torus from internal concentrations of masses on opposite parts of the wheel. Glass windows mounted on aluminum ribs cover 1/3 of the surface of the torus and admit sunlight "downward" onto the agricultural and residential areas. The remaining 2/3 of the shell of the torus is constructed of aluminum plates. Details are given in appendix A.

Passive shielding against cosmic rays is a separate, unconnected shell with a gap of approximately 1-1/2 m between it and the torus. The shield, 1.7 m thick, is constructed from large "bricks" of fused undifferentiated lunar soil held together by mechanical fasteners. Over the window region the shield is shaped in the form of "chevrons" with mirrored surfaces which pass light by a succession of reflections but block cosmic rays. The shield and chevron configuration is illustrated in figure 5-2. (For a more detailed explanation see appendices E and K.)

If the shield is used as a reaction mass during spin-up of the torus it would counter-rotate at approximately 0.07 rpm; the relative velocity between the shield and the torus, would thus be about 100 m/s. The torus is prevented from scraping against the shield by a positive positioning device.

The stationary main mirror located above the docking area of the space colony reflects sunlight parallel to the axis of rotation onto the rotating ring of secondary mirrors which illuminate the windows (see figs. 5-1 and 5-2). The secondary mirrors are segmented and each segment is individually directed to regulate the amount of light entering the habitat. The flux of light in space is 1400 W/m^2, but requirements in the torus vary from 200 W/m^2 in the residential areas to 1000 W/m^2 in the agricultural areas. Furthermore, a diurnal cycle is required in residential and some agricultural areas, while other agricultural regions require continuous solar radiation. This is achieved by directing the light away from certain windows to obtain darkness and by concentrating the light from several mirrors onto other windows to meet the high flux demands.

As your ship moves smoothly toward the docking area, you become aware of the details of this gigantic wheel-like structure. You see the 100-m-diam fabrication sphere on the "south" side of the central hub. Your companion tells you this is where metals are shaped and formed and where much of the assembly and construction takes place. To one side of the fabrication sphere is a 200 MW solar power plant and furnace used in fabrication; in the opposite direction you see the dimly visible 4.9×10^5 m^2 expanse of the habitat's radiator with its edge toward the Sun. It radiates into space the waste heat of the habitat delivered to it by a complex of heat exchangers passing through the spokes from the torus to the hub. Like the docking area at the North Pole, the fabrication sphere and radiator do not rotate. (See fig. 5-3.)

As the IOTV passes over the spokes toward the hub you see areas of silicon solar cells suspended between the spokes, central hub, and secondary mirrors. Because they look northward toward the main mirror, these cells are sheltered by the other mirrors from the degrading effects of the solar wind. Your

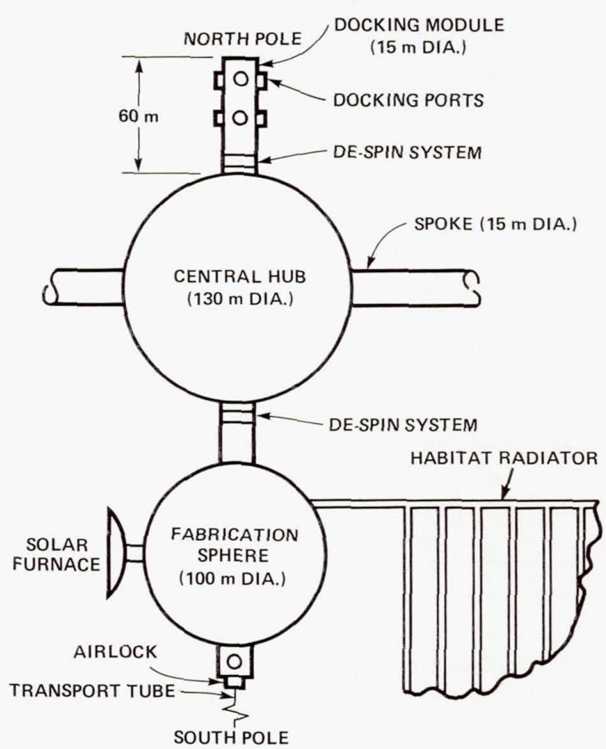


Figure 5-3.– *Hub configuration.*

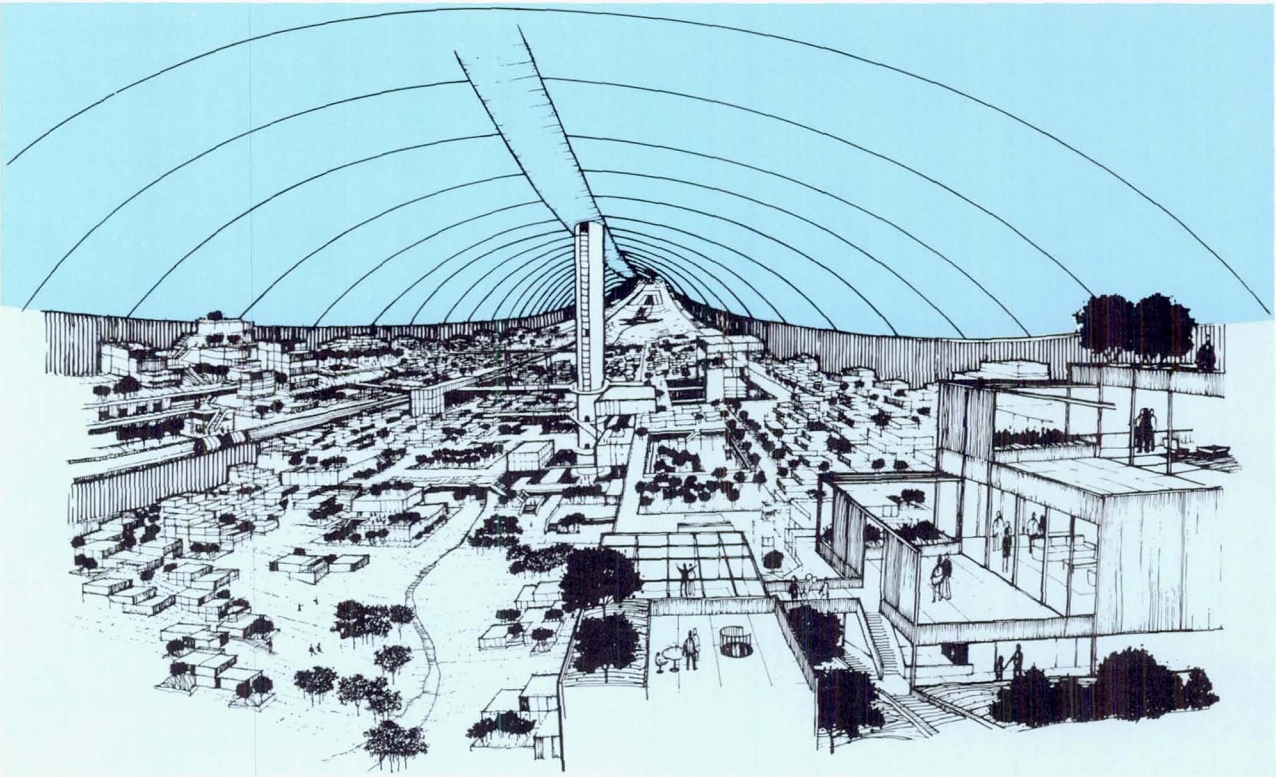


Figure 5-4.– *View of the interior.*

fellow passenger tells you they supply 50 MW of electric power required by the habitat. If control of the main mirror were accidently lost or some other accident should cause loss of solar power, the 200 MW solar power station at the extraction facility, some 10 km from the South Pole, would supply emergency power.

The IOTV moves almost imperceptibly through the last few meters and gently attaches itself to one of the docking ports. All people and equipment for the habitat pass through these ports. There is an unexpected lack of officials and there are no landing formalities. One agent oversees unloading; a second acts as a guide to the passengers. Labor is scarce so that the colony cannot support a bureaucracy, explains your companion.

Passing from the docking module, you see the walls of the central hub moving slowly by you as you float freely under zero-g. You are now in the rotating habitat, but because you are near the axis of rotation, the rotation rate of 1 rpm gives no appreciable sensation of weight. In fact, a few workers on their lunch break can be seen cavorting in the almost zero-g of the central hub playing an unusual type of ballgame, invented by earlier construction workers.

The hub is, however, much more than a playground, it is a crucial crossroads for the whole colony. Six spokes converge from the torus to this 130-m-diam sphere and emerge from its walls. They carry the power cables and heat exchangers that connect the interior of the habitat to the external power supplies and the radiator. They also serve as elevator shafts through which several thousand commuters travel each day to and from their work in the fabrication sphere or outside the habitat. Now with the other new arrivals you enter an elevator in one of these spokes and begin the 830-m trip out to the torus. As the elevator moves and the sense of "gravity" begins, you realize that "out" is really "down."

A Residential Area

Emerging from the elevator your fellow passengers go their various ways as you enter a busy community without skyscrapers and freeways; a city which does not dwarf its inhabitants. The human scale of the architecture is emphasized by the long lines of sight, the frequent clusters of small fruit trees and parks, and the sense of openness produced by the broad expanse of yellow sunlight streaming down from far

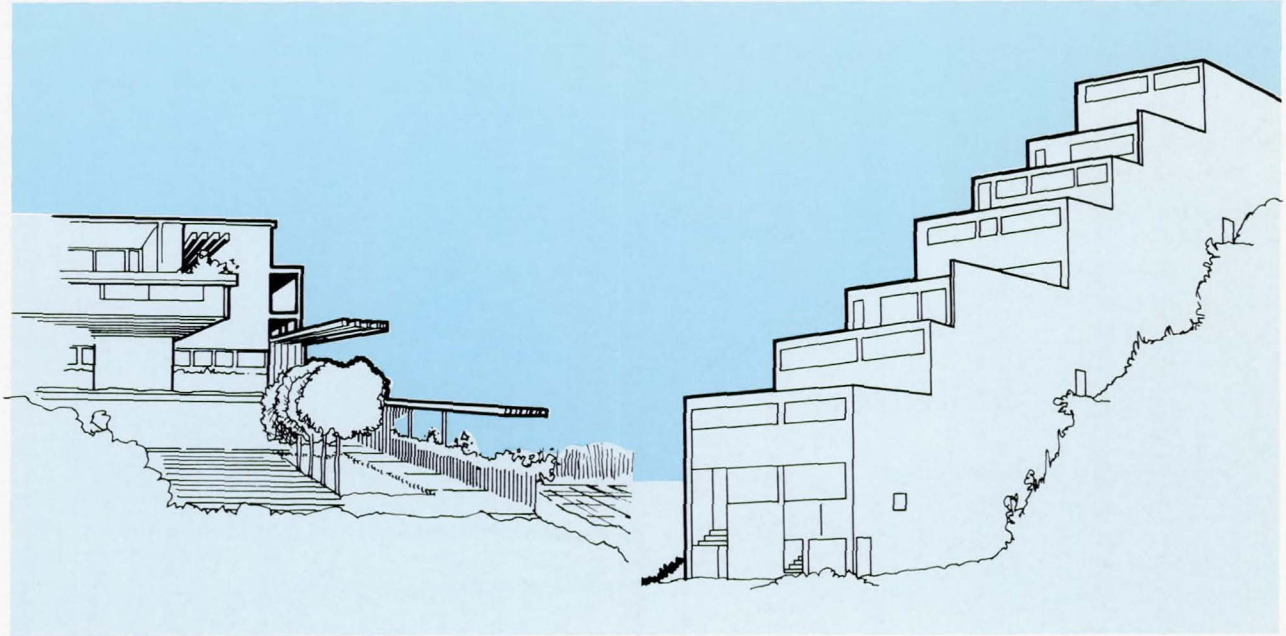


Figure 5-5.– *Terrace housing application exterior views.*

overhead. This is the central plain running the full circumference of the torus along the middle of the tube.

Houses are the most numerous structures. You are impressed by the architectural achievement in housing 10,000 people on 43 ha (106 acres) while maintaining a spacious environment. Spaciousness is achieved by terracing structures up the curved walls of the torus and also by placing much of the commerce (e.g., large shops, light industry, mechanical subsystems) in the volume of the torus which lies below the central plain on which most inhabitants live. Houses have plenty of window area to provide a sense of openness. Walls and doors are only needed for acoustical and visual privacy and not for protection from the weather.

Housing in the space colony (see fig. 5-4) is modular, permitting a variety of spaces and forms – clusters of one- or two-level homes, groups of structures as high as four and five stories, and terraced homes along the edges of the plain. Use of the modular components is illustrated in figures 5-5 to 5-7. (For more information see appendix B.)

As noted in chapters 2 and 3 the total projected area (defined in appendix B of ch. 3) required in the torus is 43 m^2/person for residential and community life, 4 m^2/person for mechanical and life support subsystems, and 20 m^2/person for agriculture and food processing. Figure 5-8 (overleaf) illustrates these projected areas in terms of total surface area and the number of levels required for each function. By making use of multiple layers above and below the central plain, the apparent population density in the colony is reduced. Layers below the central plain are illuminated artificially. Figure 5-9, a longitudinal section of the toroid's tube, illustrates schematically the layers of the colony below the central plain. All the architecture within the enclosure of the torus must be distributed to satisfy several requirements: 1) the need for residences to be near the transportation spokes to the hub, 2) the need to balance masses around the rim of the torus, 3) the desirability of acoustically isolating residential areas from noisy commercial and service activities, 4) the need for fire prevention, and 5) the need to facilitate pedestrian traffic.

The total projected area within the torus is 678,000 m^2. If the height between decks is 15 m, the volume needed for agriculture and life support is 10×10^6 m^3. A volume of 8×10^6 m^3 needed for residential and community living brings the total volume (18×10^6 m^3) to only 26 percent of the total of 69×10^6 m^3 which is enclosed by the torus. The "extra" 74 percent of the volume helps to reduce the apparent population density. The areas and volumes required and available are summarized in table 5-1 (page 94).

You are aware that the colony has filled up over the preceding 4 yr at the rate of about 2000 people

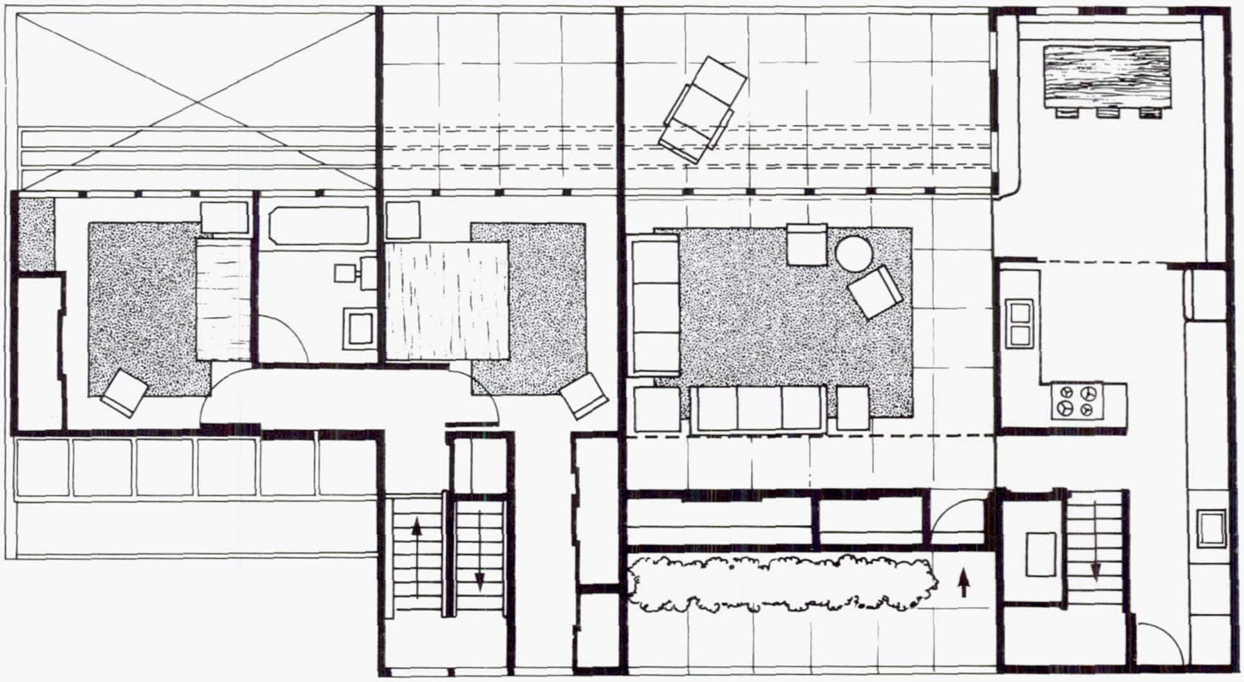


Figure 5-6.– *A possible apartment plan.*

Figure 5-7.– *View of housing.*

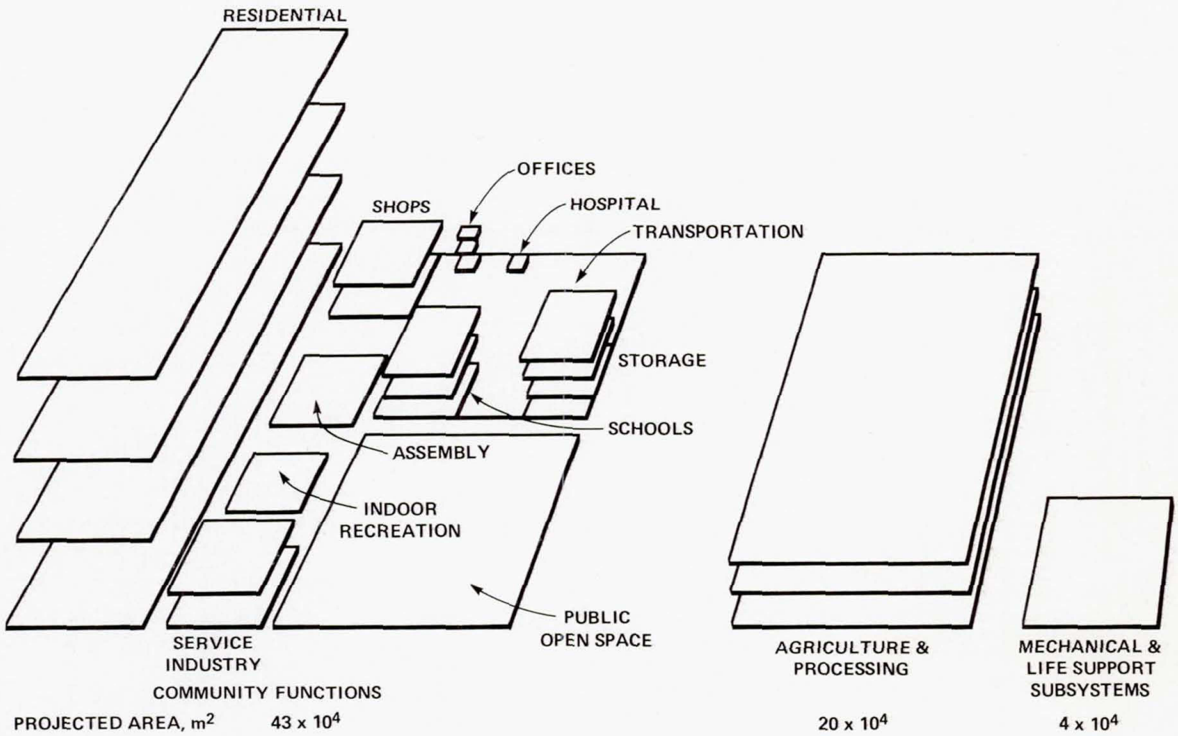


Figure 5-8.– *Allocation of space in the colony.*

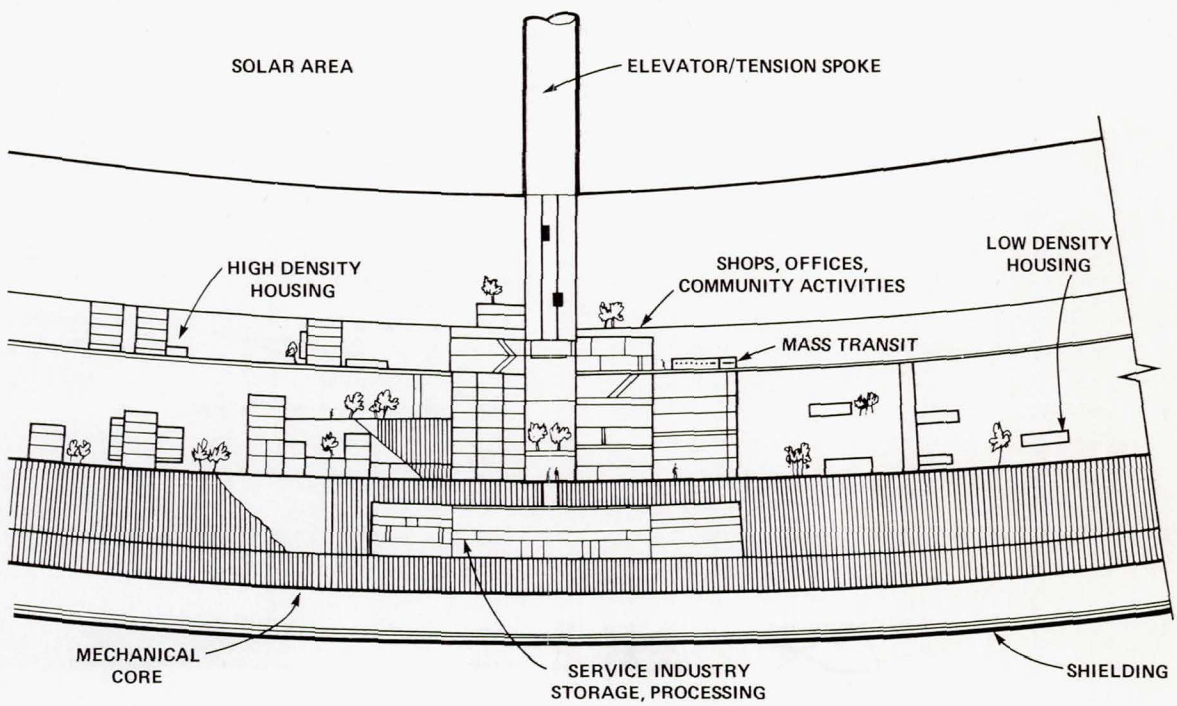


Figure 5-9.– *Partial longitudinal section.*

TABLE 5-1.– FUNCTIONAL DISTRIBUTIONS OF AREAS AND VOLUMES IN THE STANFORD TORUS

Description	Surface area, m^2	Projected area, m^2	Volume, m^3
Community area	980,000	430,000	8×10^6
Agriculture, processing and mechanical	650,000	240,000	10×10^6
Total required	1,680,000	670,000	18×10^6
Total available	---	678,000	69×10^6

per year. Consequently, the houses close to the elevator are already occupied. Since you are a latecomer and also only a temporary visitor, your apartment is some 400 m from where you enter into the torus. This is about the greatest distance anyone resides from an elevator, and the walk takes only 5 min. You might buy a bicycle if you were staying longer. Alternatively you can choose to walk 60 m to the ring road which passes around the torus at the edge of the plain and catch a transport car to the stop nearest your destination. Since you are a tourist and want to see what is going on, you decide to walk and start off down a tree-lined pedestrian way following the directions on the map you were given when you landed.

Equally as striking as the lack of traffic and wide roads is the presence of a flourishing vegetation. Stimulated by plentiful sunshine, brilliantly colored flowers bloom in profusion along winding walkways. You meet a colonist heading in the same direction as yourself. She tells you she is an engineer at the habitat controls center and is one of those responsible for the maintenance, modification, and control of the mechanical and electrical systems. A few questions about this gigantic and complex structure bring forth a flood of information from your companion. To resist the atmospheric pressure and the centrifugal forces of its own mass as well as the internal masses, the shell has a skin thickness of 2.1 cm. The windows through which sunlight streams are some 65 m "above" you and are 2.8 cm thick. Buried in the walls and under the decks of the torus are thousands of kilometers of wires and piping for electrical power distribution, water supply, waste disposal, and air dehumidifying.

The shell of the torus is designed to resist loads of 50 kPa of atmospheric pressure and the centrifugal forces of its own mass as well as 530,000 t of internal mass. Including the ribbed portion, the mass of the aluminum shell is 156,000 t. (Details of the design are presented in appendix A.) For the windows to resist the pressure of the atmosphere across a span of 0.5 m, the distance between ribs, the glass is 2.8 cm thick. This requires 48,000 t of glass.

The masses of the main components of the habitat (except for the extraction plant) are listed in table 5-2; the principal internal masses are summarized in table 5-3.

Arriving at your apartment house you bid the other colonist goodbye. The house is a combination of two duplexes and two studio apartments (see appendix B). Each of the studio apartments on the third floor has a small balcony on which some plants are growing. On a neighbor's balcony is an impressive stand of cherry tomatoes and lettuce in a few pots. Small patios below each balcony are surrounded by dwarf apple and peach trees.

Although small (49 m^2) your apartment is completely furnished in a compact, convenient and attractive way. Furniture and the few ornaments are made of aluminum and ceramics, a constant reminder that wood and plastics must come from Earth or be made from carbon, nitrogen and hydrogen brought from Earth. It takes a while to become accustomed to the almost complete absence of wood and plastics.

Although the apartment has a kitchenette, you decide it will be more convenient and pleasant to eat in one of the neighborhood community kitchens where you can meet and get to know neighbors as you dine with them. So you walk to the closest of these kitchens.

A glance around the dining area reveals young adults and a few children. Briefings before you left Earth had informed you that the community of the space habitat consists of men and women between the ages of 18 and 40, a few hundred children who came with their parents from Earth, and about a hundred children who were born in the colony. The population mix is that of a typical terrestrial frontier – it is hardworking, concentrating intently on the manufacture of satellite solar power stations and the construction of the next colony, a replica of this one.

As you sit down to eat, one of the few colony elders tells you of the philosophy behind the productivity and growth in the colony.

TABLE 5.2.– SUMMARY OF HABITAT COMPONENT MASSES

Item	Mass, t	
	From lunar ore	From Earth
Shield	9,900,000	---
Torus shell	156,000	---
Glass solars	48,000	---
Spokes	2,400	---
Central hub	1,600	---
Docking module	100	---
Fabrication sphere	---	500
Radiators	2,400	---
Habitat power station	700	---
Main mirror	200	7 (Mylar)
Secondary mirrors	90	3 (Mylar)

TABLE 5-3.– SUMMARY OF INTERNAL MASSES

Item	Mass, t
Soil (dry) – 1,000,000 m^2, 0.3 m thick, 721 kg/m^3	220,000
Water in soil (10% soil)	22,000
Water, other	20,000
Biomass – people	600
animals	900
plants	5,000
Structures	77,000
Substructures (20% of structures)	15,000
Furniture, appliances	20,000
Machinery	40,000
Utilities	29,500
Miscellaneous (extra)	80,000
Total	530,000

Despite the narrow focus of activities in the colony, he explains, there is considerable stimulation and innovation by the new settlers. The rapid growth of the settlement sustains a sense of dynamic change; but he warns that the stabilization of the community upon reaching its full size may result in the dissipation of that sense (ref. 1). A community as small and as isolated as the colony may stagnate and decline in productivity and attractiveness. The answer to the problem is continued growth by the addition of more colonies. Growth is important economically as well as psychologically, because as time passes the population will become more like that of Earth in its age distribution, with the productive fraction of the population diminishing from about 70 percent to between 30 percent and 40 percent. If more colonies are not established, the amount of production will decrease with time. He points out that only if the total number of people grows rapidly can production in space be maintained at its initial level and be increased sufficiently to meet growing demands of Earth's markets for satellite solar power stations. Furthermore, he explains, the aggregation of habitats into larger communities will enable the colonies to develop cultural and technological diversity similar to that which permits the larger cities of Earth to be centers of innovation and disseminators of cultural and technological change.

The colony experiences the egalitarianism of a frontier reinforced by the esprit *of a group of people working together with a sense of mission on a common task. His face glowed with enthusiasm as he declared that this spirit, more than heroic adventures or romanticized challenge, is what makes the colony a rewarding place to live. Egalitarianism is tempered by certain realities within the colony. The entire colony has a sense of elitism simply because each individual colonist was selected as a settler. A distinction developing between those with clean and "shirtsleeve" jobs and those who work in hazardous, heavy industry, or zero atmosphere jobs, has only small effects and will not produce marked socio-economic differentiation for a number of years.*

He excuses himself, saying he has a meeting of the "elders" to attend.

You continue eating alone. Your meal is satisfying – chicken, peas, and rice followed by apple pie for dessert – hardly the fare which science fiction writers led you to expect. There are no dehydrated "miracle" foods or algae cake because the colony is equipped with extraordinarily productive farms that raise food familiar to people on Earth. Your interest is aroused and you decide to tour the agricultural area next to see how this food variety is achieved.

An Agricultural Area

To promote diversity and to build in redundancy for safety's sake the torus is divided into three residential areas separated by three agricultural areas. The latter is segmented into controlled zones which may be completely closed off from other zones. This arrangement permits farmers to use higher than normal temperatures, carbon dioxide levels, humidity and illumination in the

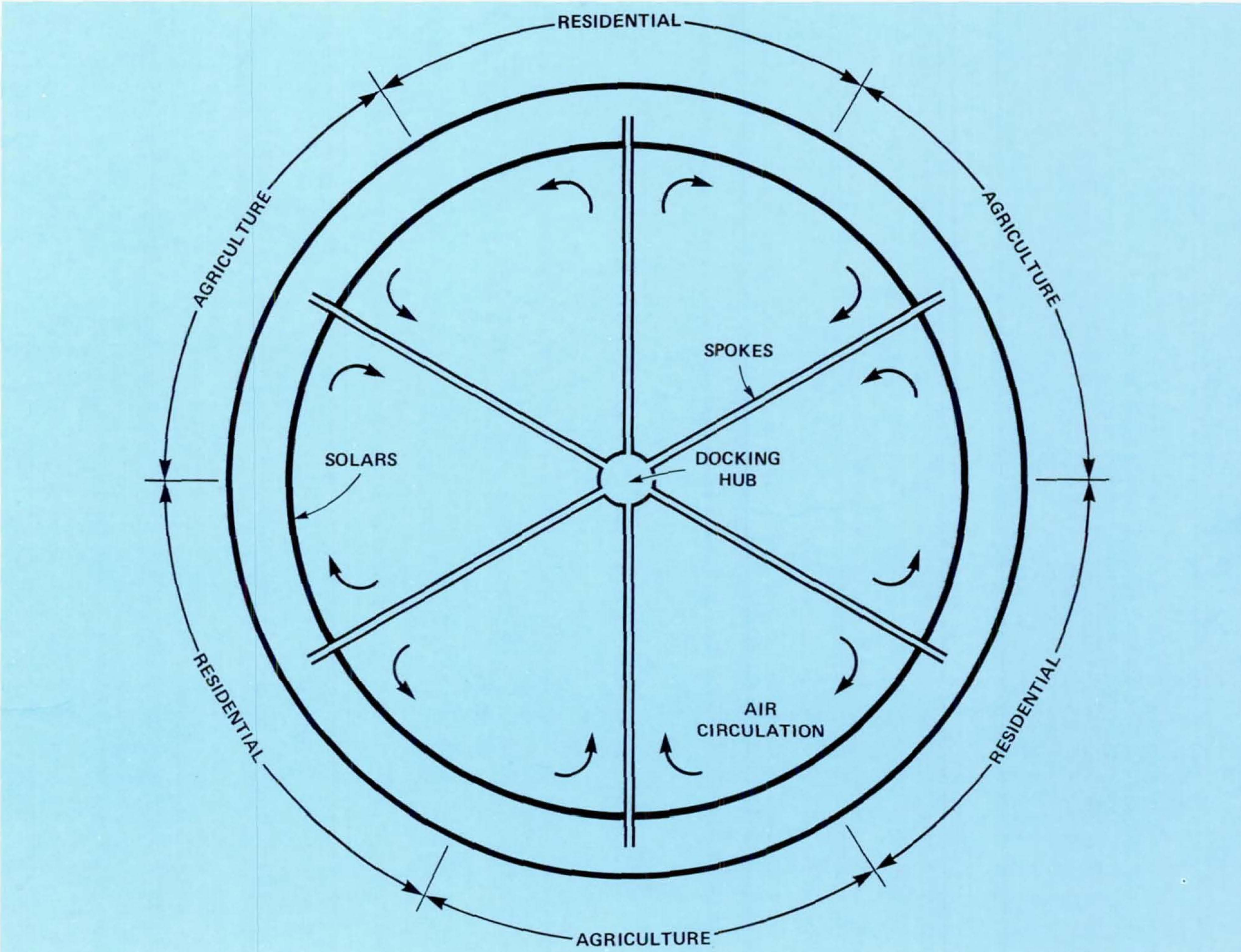


Figure 5-10.– *Section showing distribution of residential and agricultural areas.*

controlled zones to force rapid growth (fig. 5-10). Partitioning also inhibits the spread of any disease of plants or animals from one zone to another.

A couple of minutes walk brings a view of tiers of fields and ponds and cascading water (fig. 5-11). The upper level where you enter is surrounded by a number of ponds holding about 90,000 fish. There are similar ponds in the other two farms. From the ponds the water flows down to lower levels where it irrigates fields of corn, sorghum, soy beans, rice, alfalfa, and vegetables, and provides water for livestock. The multiple tiers triple the area of cropland (fig. 5-12).

On the second tier down a farmer shows you around. The wheat growing on this tier, he tells you, will be ready for harvesting next week. Each of the three agricultural areas in the colony grows essentially the same crops; however, harvests are staggered to provide a continuous supply. On another tier enormous tomatoes grow in a special control zone with elevated levels of carbon dioxide, temperature, and humidity. On one of the lower levels, the farmer impresses you with the fact that this farm, like the others contains some 20,000 chickens, 10,000 rabbits, and 500 cattle. The lowest level is enclosed and kept at very low humidity to permit rapid drying of crops to hasten produce flow from harvest to consumption. Because of its high productivity the colony's agriculture feeds 10,000 people on the produce of 61 ha (151 acres). You marvel that so fruitful a garden spot is actually in barren space, thousands of miles from any planet.

The agricultural system supplies an average person of 60 kg with 2450 cal (470 g of carbohydrates and fats and 100 g of protein) and almost 2 l of water in food

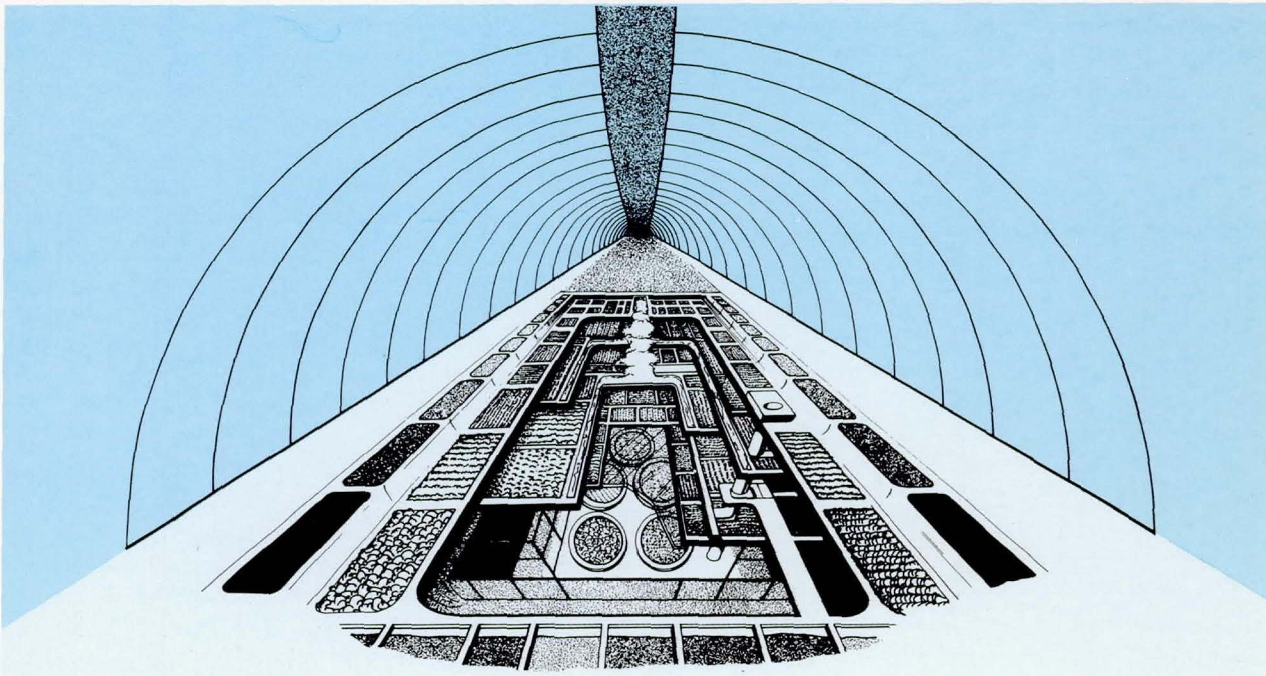


Figure 5-11.– *View of the agricultural areas. (See also frontispiece to ch. 3.)*

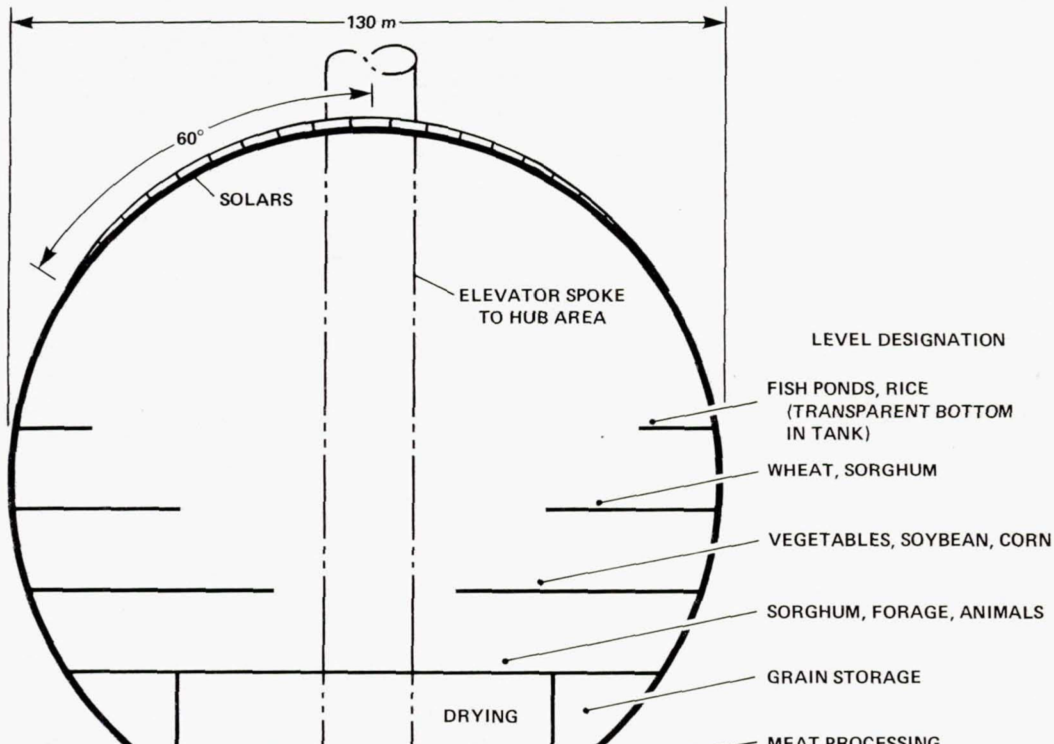


Figure 5-12.– *Cross-section of agricultural region.*

and drink each day (ref. 2). Plants and animals are chosen for their nutritional and psychological importance (ref. 3) (e.g., fresh fruits, vegetables, and beef). The principal crop plants and animals and the areas devoted to each are given in tables 5-4 and 5-5. Fruit is not included in these tabulations. The trees are grown in residential areas and parks where they provide beauty as well as fruit.

The crops are grown in a lunar soil (ref. 4) about 0.3 m deep. This soil is made into a lightweight growth matrix by foaming melted rock. The yields are greater than those achieved on Earth because of improved growing conditions and the ability to grow crops on a year-round basis. The higher levels of carbon dioxide, improved lighting, and temperature and humidity control increase productivity to approximately 10 times that of the typical American farm. Terrestrial experiments (ref. 5) have produced fivefold increase in yield for production of vegetables in controlled greenhouses. (For more details on the agricultural system, see appendix C.)

Life Support Systems

Next stop on your tour is the waste processing facility at the bottom of the agricultural area. It is an important part of the life support system because it maintains a delicate balance between the two opposing processes of agricultural production and waste reduction. A sanitation technician explains the operation of the facility.

He points out that on Earth production and waste reduction are balanced, at least partly, by natural processes. Water is extracted from the atmosphere by precipitation as rain; biodegradable materials are reduced by bacterial action. In space neither of these processes is fast nor reliable enough. The colony, lacking oceans and an extensive atmosphere in which to hold wastes, is limited in its capacity for biomass and cannot duplicate Earth's natural recycling processes. Instead, it uses mechanical condensation of atmospheric moisture and chemical oxidation of wastes to reduce the recycling time to 1-1/2 hr. This approach minimizes the extra inventory of plants and animals necessary to sustain life and to provide a buffer against breakdowns in the system.

Agriculture uses sunlight, carbon dioxide, and chemical nutrients to produce vegetation and from that, to raise animals. Oxygen and water vapor released as byproducts regenerate the atmosphere and raise its humidity. A considerable amount of vegetable and animal waste is produced along with human wastes of various kinds – sewage, exhaled carbon dioxide, and industrial byproducts – and all these have to be recycled.

TABLE 5-4.– PLANT AREAS

	Amount required, g/person/day	Yield, g/m^2/day	Area, m^2/person
Sorghum	317	83	3.8
Soybeans	470	20	23.5
Wheat	225	31	7.2
Rice	125	35	3.6
Corn	50	58	.9
Vegetables	687	132	5.2
Totals	1874	359	44.2

Notes: Fruit in colony provides 250 g/person/day.
Grains and soybeans – dry weights.
Sugar is obtained from sorghum, perhaps from honey.
Cattle use part of the plant roughage.

TABLE 5-5.– ANIMAL AREAS

Animal	Number/ person	Area/ animal, m^2	Area/ person, m^2
Fish	26	0.1	2.6
Chickens	6.2	.13	.8
Rabbits	2.8	.4	1.1
Cattle	.15	4.0	.6
Total			5.1

Notes: Sources for areas required per animal.

Fish: Bardach, J. E.; Ryther, J. H.; McLarney, W. O.: *Aquaculture*: The Farming and Husbandry of Freshwater & Marine Organisms. © 1972 (Wiley-Interscience: New York).

Chickens: Dugan, G. L.; Golueke, C. G.; Oswald, W. J.; and Risford, C. E.: Photosynthesis Reclamation of Agricultural Solids and Liquid Wastes, SERL Report No. 70-1, University of California, Berkeley, 1970.

Rabbits: Henson, H. K., and Henson, C. M.: Closed Ecosystems of High Agricultural Yield, Princeton Conference on Space Manufacturing Facilities, May, 1975.

Cattle: Kissner, Wm.: Dept. of Civil Engineering, University of Wisconsin – Platteville: Personal Communications.

Waste processing restores to the atmosphere the carbon dioxide used up by the plants, reclaims plant and animal nutrients from the waste materials, and extracts water vapor from the atmosphere to control the humidity of the entire habitat and to obtain water for drinking, irrigation, and waste processing. He tells you that balancing waste generation and waste reduction is a major accomplishment of the designers of the colony, for it eliminates any need to remove excess wastes from the habitat thereby avoiding having to replace them with expensive new material from Earth.

The technician explains that water is processed at two points in the system. Potable water for humans and animals is obtained by condensation from the air. Because evapotranspiration from plants accounts for 95 percent of the atmospheric moisture, most dehumidifiers are located in the agricultural areas. Because of the rapidity with which plants replace the extracted water it is important that the dehumidification system be reliable. Otherwise the air would quickly saturate, leading to condensation on cool surfaces, the growth of molds and fungi, and an extremely uncomfortable environment. Several subunits are used for dehumidification.

The dehumidifiers work in conjunction with the heat exchange system which carries excess heat from the habitat to the radiator at the hub. For water condensation in the torus' gravitational field, normal condensation techniques are used. Figure 5-13 shows schematically (ref. 6) how water is removed in zero-g areas such as the hub. The humidity is controlled by varying the temperature of the coolant and the rate at which air is passed through the unit. To cool and dehumidify it, the atmosphere must be passed through a thermal processor several times per day.

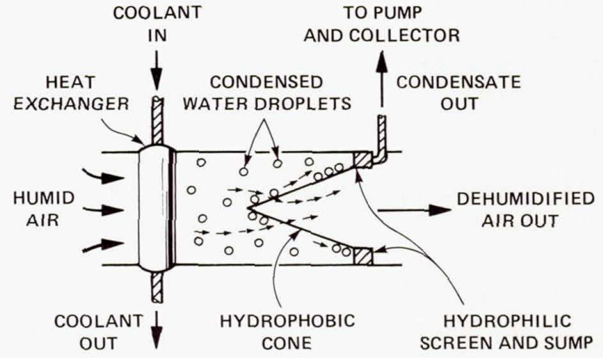


Figure 5-13.– *Water removal.*

Water is also a byproduct of the continuous wet oxidation process (ref. 7) shown schematically in figure 5-14.

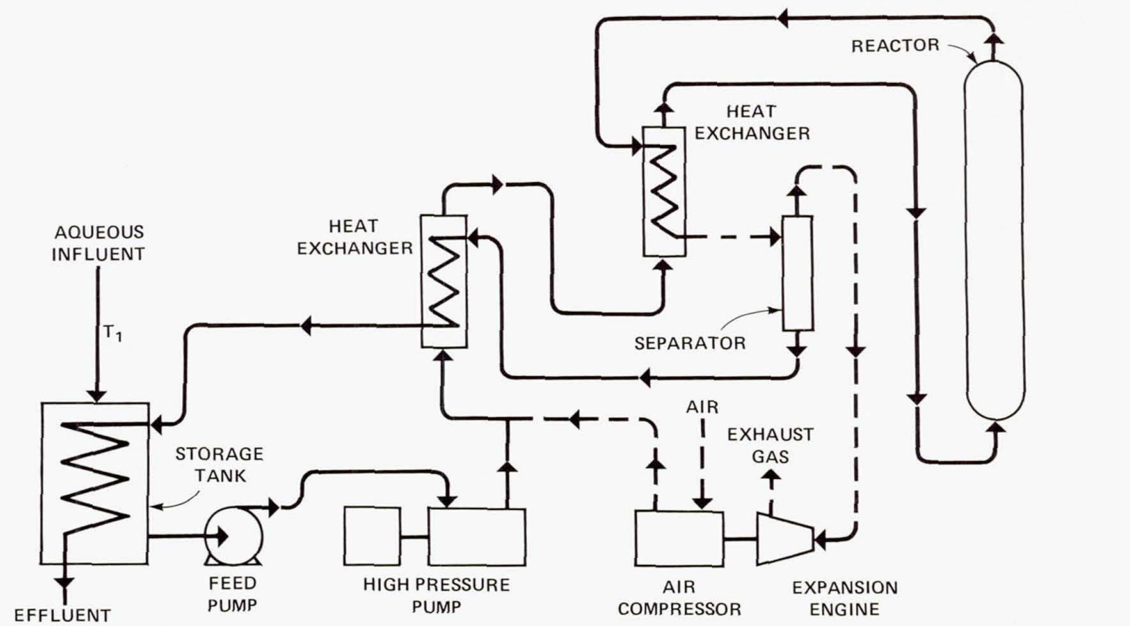
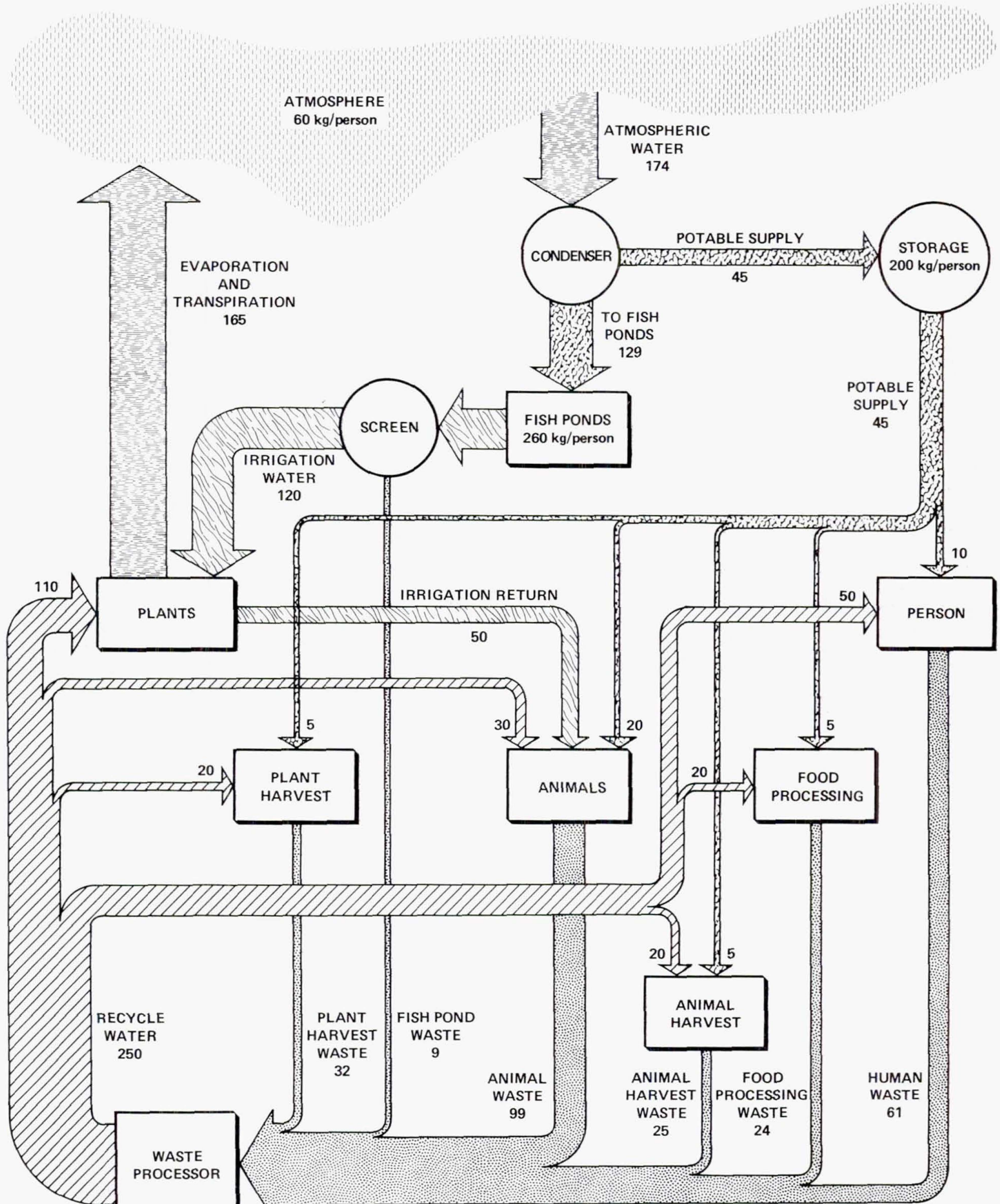


Figure 5-14.– *Continuous wet oxidation process.*



NOTE: INDIVIDUAL COMPONENTS DO NOT BALANCE AS WATER OF EVAPORATION AND RESPIRATION OR RECONSTITUTED IN FOOD IS NOT SHOWN BUT WASTE MATTER IS INCLUDED IN THE FIGURE.

Figure 5-15.– *Dual water supply, kg/person/day.*

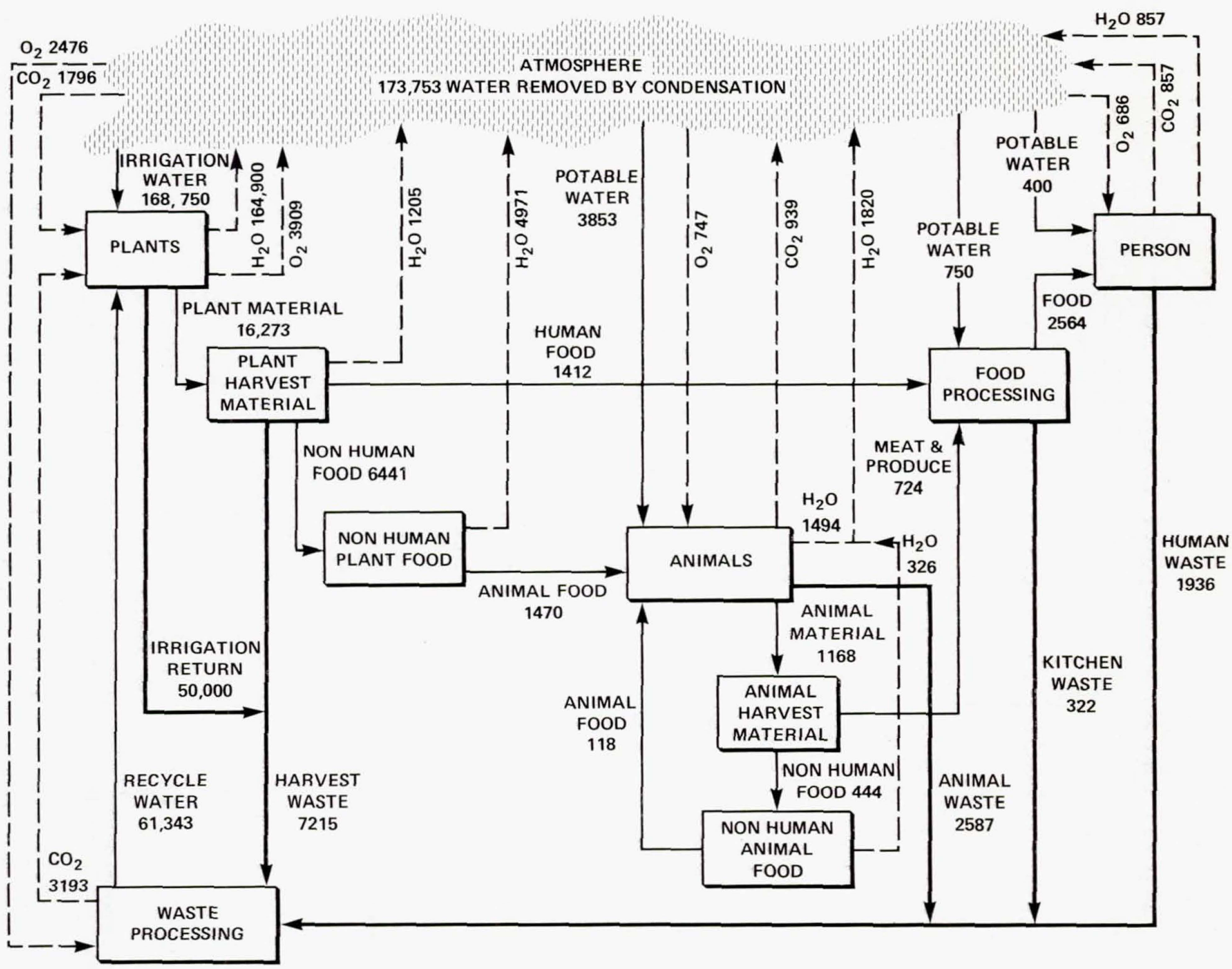


Figure 5-16.– *Life support mass balance, g/person/day.*

The complete water supply illustrated in figure 5-15 provides 25 times the potable water needed to satisfy the metabolic requirements of the colonists and their animals. (Figure 5-16 considers only metabolic requirements and does not include water for waste transport.) In addition, some 250 kg of recycled water per person per day is used for waste transport. In spite of this extensive dilution, the total per capita water use in the colony is only 75 percent of U.S. domestic water usage. Consumption is limited by use of recirculating showers, low volume lavatories, and efficient use of water in food preparation and waste disposal. Any increase in water for waste transport reduces the amount of condensed atmospheric water which can be used for irrigation, and increases the recycle water. In addition, 200 kg/person of water is set aside for emergencies and fire protection.

Water condensed from the air is heated to 16° C and fed into the fish ponds. After flowing through the ponds, the water is continuously screened to remove fish waste, mixed with warm recycled waste water, and used for irrigation. Since the water drains through soil and collects under the "field" it is further used to transport animal and human wastes to the waste processing facility.

The temperature difference of the influent and effluent for waste processing is 34.5° C. Heat exchangers are used with the cool, condensed atmospheric water and the recycled water to reduce the cooling necessary for recycled water to 22.2 MJ/person/day. (See fig. 5-17.)

In addition to water the wet oxidation process produces exhaust gases rich in carbon dioxide which are scrubbed to remove trace contaminants. The carbon

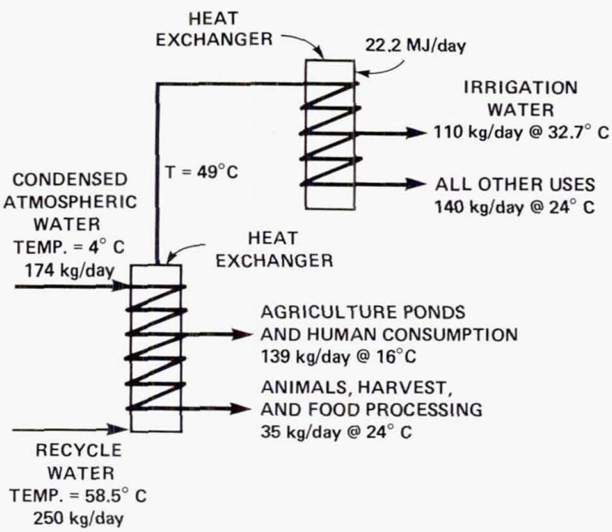


Figure 5-17.– *Heat balance of water supply, per person.*

dioxide is fed into the agricultural areas to maintain high concentrations and improve agricultural yields. Solids in the effluent are filtered and returned to the system as animal feed and fertilizer. A high concentration of solids is desirable to make the wet oxidation reaction self sustaining; that is, the difference in temperature between the effluent and influent depends upon the concentration and heat value of the solids. The balance between mass input and output to permit the life support system of the colony to operate in a closed loop is shown in figure 5-16.

The flow of energy in the colony is of major importance since energy is required both for production of manufactured goods and for agriculture, and the waste heat must be removed by radiators. In addition, industrial processes and the normal amenities of life (e.g., stoves, refrigerators, and other appliances) require electrical energy, the heat of which must also be removed.

Within the habitat itself the largest energy input is the insolation of the agricultural areas (the bulk of which is transferred to water evaporated from the foliage) and

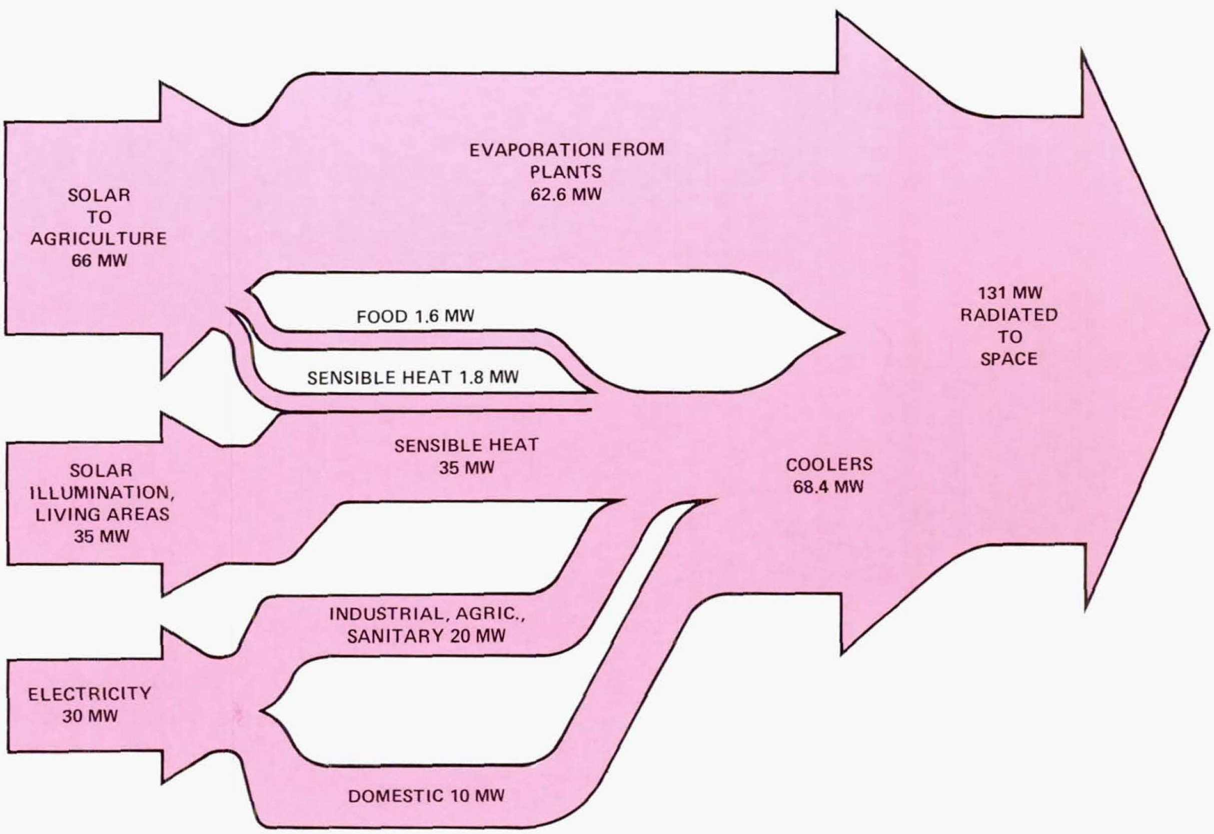


Figure 5-18.– *Energy flow in the colony.*

the residential areas (see fig. 5-18). A smaller but significant portion of the total input is the electrical power supplied to the colony from its solar-electric power station. The habitat's electrical power consumption per capita is 3 kW, a figure obtained by doubling that of the current U.S. per capita consumption to account for the need to recycle all materials in the colony.

The energy removed from the atmosphere is transferred to the working fluid of the radiator. Assuming a radiator temperature of 280 K, corresponding to a black body radiation of 348 W/m^2, the required area of a 60 percent effective radiator is 6.3×10^5 m^2. An increase of 50 percent in the area to handle peak daytime solar loads is appropriate; therefore, the required area is 9.4×10^5 m^2. Woodcock's estimate (ref. 10) of 2.5 kg/m^2 for the mass of a radiator leads to the habitat requiring 2400 t of radiator mass.

PRODUCTION AT L_5

Stopping for a mug of Space Blitz *on the way back to your apartment you happen to catch the Princeton-Stanford ball gàme on television from Earth and learn that, to everyone at the bar, the three-dimensional ball game played in the central hub is much more thrilling. You find that really only the name of the game played at the colony is the same since the liberating effects of low gravity and the Coriolis accelerations make all shots longer, faster, and curved, thus completely changing the rules and the tactics of the game.*

Later the TV news carries a story on difficulties encountered in building the new SSPS. There have been several unforeseen problems with all phases of the production process but in particular with the extraction facility which, to avoid pollution of heavy industry and to isolate a possible source of industrial accident from the habitat, is placed outside the habitat, south of the hub some 10 km away. Although the plant is operated remotely so that it can be left exposed to the vacuum of space, there are a number of small spheres attached to the plant where maintenance can be performed in a "shirt sleeve" environment. The plant has its own solar furnaces and a 200 MW electric power station run by solar energy. Bulk products such as aluminum ingots, oxygen gas, plate glass, expanded soil and shielding material, are brought to the fabrication sphere by small tugs. However, small items and people make the trip through a pressurized transport tube which seems to be developing structural problems near its remote end. In the bar, a construction foreman tells you he is convinced the problem derives from torsional fatigue, but no one seems to be worried since many such problems in the system have been quickly solved in the past. On learning you are a newcomer the foreman offers to act as guide on a quick visit to the fabrication facilities where the major effort of the colony is concentrated and, if possible, down the connecting tube to the extraction plant. Pleading fatigue you head home. At your apartment, you put your feet up and read some descriptive material on the fabrication facilities.

Productivity in Space Construction

Productivity in space is difficult to estimate (see appendix D). The zero g and high vacuum in some situations increases productivity above that obtainable on Earth and decreases it in others. The only basis for estimation is experience on Earth where the models of industrial productivity used are based on factors of man-hours of labor per kilogram, per meter, per cubic meter, etc. Table 5-6 presents estimates of productivity of humans performing some basic operations of industry and construction. These numbers were derived from estimating factors commonly used on Earth (ref. 8) in 1975, which were modified somewhat on the basis of limited experience in the space program.

Generally, because cost estimating factors are closely guarded proprietary figures in terrestrial industry, reliable information is difficult to obtain. Therefore, the estimates in table 5-6 are used, recognizing appreciable uncertainty in their values. A more detailed discussion of estimated productivity is given in appendix D.

Manufacture of Satellite Solar Power Stations

In addition to constructing new colonies, the manufacture of satellite solar power stations is the second major industry. Such power stations provide the chief

TABLE 5-6.– REPRESENTATIVE PRODUCTIVITIES

Industry or product	Productivity
Primary aluminum (Hall process)	97 kg/man-hr
Titanium mill shapes	8.8 kg/man-hr
Household freezers	20 kg/man-hr
Light frame steel erection	28.57 kg/man-hr
Piping, heavy industrial	0.26 m/man-hr

commercial justification of the colony. Placed in geosynchronous orbit they satisfy the Earth's rapidly increasing demand for electrical energy by capturing the energy streaming from the Sun into space and transmitting it to Earth as microwaves where it is converted to electricity and fed into the power grids. While such satellite power stations could be built on Earth and then placed in orbit (refs. 9 and 10), construction in space with materials from the Moon avoids the great expense of launching such a massive and complex system from Earth to geosynchronous orbit. The savings more than offset the higher costs of construction in space.

Analysis shows that 2950 man-years are needed to build a satellite solar power station to deliver 10 GW to Earth. A summary of the man-years required for different options for constructing part of the system on Earth and part in space, or for using a photovoltaic system rather than a turbogenerator, is given in table 5-7.

Other Commerce

There are commercial activities of the colony other than those of constructing satellite solar power stations or new colonies. The easy access to geosynchronous orbit from L_5 puts the colonists in the satellite repair business. Communications satellites, which otherwise might be abandoned when they fail, can be visited and repaired. Furthermore, the solar power stations themselves require some maintenance and may even have crews of from 6 to 30 people who are periodically rotated home to L_5.

TABLE 5-7.– OFF EARTH LABOR REQUIREMENTS FOR SPSS'S

	Labor, man-years
Thermal SPSS, 10 GW	
Complete SPSS	2950
Generator (SPSS w/o transmission)	1760
Heating furnace only	1600
Photovoltaic SPSS, 5 GW	
Complete SPSS	2540
Generator (SPSS w/o transmission)	1800

Notes: Assumes the use of lunar material in productive facilities already in place and high-technology equipment supplied from Earth. The thermal data are based on Woodcock (see ref. 26, ch. 4) and the photovoltaic data on Glaser (see Ref. 25, ch. 4).

There are also commercial possibilities only just being appreciated. In high vacuum and zero g adhesion and cohesion effects dominate the behavior of molten material. Products such as metal foams and single crystals are more easily made in space than on Earth. In fact in 1975 McDonnell Douglas Astronautics Company (ref. 11) concluded that the growing of single-crystal silicon strip using an unmanned space factory would be economically advantageous.

Certain features are common to all commercial ventures in space. High cost of transportation makes shipment of goods to Earth from space uneconomical except for products with a high value per unit mass that are impossible to make on Earth. Advantages of high vacuum and reduced weight often enhance productivity. Availability of large quantities of low-cost solar energy permits production processes in space which consume such large amounts of energy that they are impractical on Earth. The expense of providing human workers encourages reliance on automation which, because of the expense of repairs and maintenance, is pushed to extremes of reliability and maintainability. The expense of replacing lost mass places strong emphasis on making all production processes closed loops so that there is very little waste.

Extraction Processes for Lunar Ores

Production at L_5 is strongly influenced by the processes available by which to refine needed materials from the lunar ores. These processes in turn specify the mass of ore required, necessary inventories of processing chemicals, and masses of processing plant.

Figure 4-25 depicts the sequence of processing to produce aluminum from lunar soil. The soil is melted in a solar furnace at a temperature of 2000 K then quenched in water to a glass. The product is separated in a centrifuge and the resultant steam condensed in radiators. (Table 5-8 lists the process radiators and their

TABLE 5-8.– RADIATORS FOR PROCESS COOLING

Process	Temperature, K	Power, MW	Area, $m^2 \times 10^3$	Mass, t
Quench	363	20.9	24	144
Acid leach	363	7.1	8.1	49
Acid cooking	363	38.3	44	262
Leach water	283	7.9	21.8	131
Chlorination	1123	10.1	.6	4
Electrolysis	973	23.1	2.6	15
Carbon reform	1123	19.8	1.3	8
Total	---	127.2	102.4	613

sizes.) The glass is ground to 65 mesh and leached with sulfuric acid. The pregnant solution containing aluminum sulfate is separated from the waste material in a centrifuge and then autoclaved at 473 K with sodium sulfate to precipitate sodium aluminum sulfate. This separation again requires centrifugation. The precipitate is calcined to yield alumina and sodium sulfate, the latter washed out with water and then the hydrated alumina calcined and coked. The mixture of alumina and carbon is reacted with chloride to produce aluminum chloride and carbon dioxide. The aluminum chloride is electrolyzed to yield aluminum. The melt-quench process with acid leaching was studied and experimentally demonstrated by the U.S. Bureau of Mines (ref. 12). The carbochlorination and electrolysis processes were developed and patented by the Aluminum Company of America (refs. 13–17).

The following four tables (5-9 to 5-12) present the logistical requirements of a processing plant capable of producing about 150 t/day of aluminum, that is, about 54 kt/yr.

The electrical requirements of the system are summarized in table 5-9, while the solar heating requirements are given in table 5-10. Table 5-11 indicates the mass inventory for process chemicals as determined by detailed evaluation of the flow chart. The equipment masses were determined through discussion with industrial contacts. The mass of the entire system is presented in table 5-12.

TABLE 5-9.– ELECTRICAL POWER REQUIREMENTS FOR PRODUCING ALUMINUM

Process	Power, MW
Electrolysis	70
Carbon reform	40
Other	5
Total	115

TABLE 5-11.– MASS INVENTORY FOR PROCESS CHEMICALS

Chemical	Mass, t	Mass excluding oxygen, t
H_2O	225	28
H_2SO_4	55	19
Na_2SO_4	30	17
NaCl	235	235
LiCl	70	70
Cl_2	25	25
Carbon	2	2
Totals	642	396

Relations to Earth

Tired of reading the technical literature, you still find it difficult to fall asleep in this new world which is so much like Earth superficially yet completely man-made. It is clear that this space colony of people with new life styles, interests and visions of the future is still tied to the Earth economically. You decide that it is, in fact, the commercial activities of the colony and economic relations to Earth which explain several of the striking features of life at L_5. Long term economic self-sufficiency and growth require manufacture of products sufficiently useful to Earth to attract capital and, ultimately, to create a favorable balance of trade in which the value of exports exceeds that of imports. While great effort is concentrated on construction of solar power plants

TABLE 5-10.– SOLAR HEATING REQUIREMENTS FOR ALUMINUM REFINERY

Process	Power, MW	Temp., K	Mirror projected area, $m^2 \times 10^3$
Melt	27	1973	19
Autoclave	32	473	23
Decomposition	12	1173	9
Calcination	5	1073	5
Totals	76		56

TABLE 5-12.– MASS REQUIRED FOR REFINING

Item	Mass, t
Structure	500
Chemicals	650
Equipment	3000
Radiators	600
Flare shield	50
Solar furnace	20
Powerplant	2800
Total	7620

and new colonies, the colonists also seek to minimize imports by producing goods for internal consumption and by maintaining a major recycling industry. The conflict between using resources and manpower for production for internal use and using them for production for export calls for many management decisions. In these early years of the colony the balance seems to be definitely in favor of production for export. Consequently, reliance on Earth as a source of the products and services of highly developed technology as well as for carbon, nitrogen, and hydrogen continues to be great. Moreover, concentration on exports greatly limits the diversity of human enterprise in the colony, because the majority of productive workers are engaged in heavy construction. Like most of the frontier communities in history, the colonists at L_5 are chiefly concerned with repaying borrowed capital, increasing their standard of living, and expanding their foothold to develop further their mastery over the environment of space.

Finally, you drift off in sleep, dreaming of yourself as an early American pioneer, clearing a small stand of trees for your new farm.

THE LUNAR BASE

After several days of touring the colony you have been continually reminded of the role of the Moon. The soil in which food is grown came from the Moon. The aluminum used throughout the colony for construction once was part of lunar ore. Even the oxygen you breathe has been extracted from lunar rocks. During the construction of this colony 1 million tonnes of lunar ore were shipped each year, and the colony still processes roughly the same amount annually to construct new colonies and satellite solar power stations.

The mining and transport of this material on and from the Moon is a major part of a successfully functioning system for space colonization. You accept an invitation to travel to the Lunar Base, and start at the module at the colony's North Pole where you board an IOTV carrying supplies to the Lunar Base. The same type of transport vehicle brought you from low Earth orbit to L_5 in 5 days; however, it takes about 2 weeks to reach the Moon from L_5.

The Site of the Lunar Base

When the IOTV has entered lunar parking orbit, it is joined by a smaller ship known as the LLV (lunar landing vehicle). You transfer to it through a docking port and then the LLV descends to the lunar surface in a few minutes and settles gently down with the retrorockets creating a huge cloud of dust which settles back to the surface quickly in the absence of any atmosphere. You have arrived at the Lunar Base. (For more information concerning the impact on the lunar atmosphere, see appendix G.)

You join several off-duty staff members in the lounge of the lunar base for a snack and a cup of coffee. The base provides many services to the people operating on 2-yr tours of duty. These services include recreational facilities, private apartments, and an excellent dining hall – to make their stay as pleasant as possible. Living conditions at the lunar mining base while comfortable reflect those of a workcamp rather than a family habitat. The base is a monolithic structure composed of prefabricated units. It is covered with lunar soil 5 m deep to protect it against meteorites, thermal fluctuations, and ionizing radiation.

Since primary activities here are mining ore, compacting the ore and launching it to L_2 (the base also supports exploration and research efforts), you are anxious to see the facilities. Walking in the Moon's weak gravitational field is so effortless that you are quite willing to don a spacesuit and join the base commander in a walking tour outside the pressurized area of the base.

Mining and Processing Ore for Shipment

Soon you arrive at the edge of a large hole in the lunar surface which is now almost 2 km across and 10 m deep, from which the ore is scooped.

The base commander explains that to supply the 1 million tonnes per year to L_5 a surface area the size of about 8 football fields must be mined each year. The mining machinery operates 50 percent of the time, requiring a mining rate of about 4 t/min (about 1 m^3/min).

Soil is scooped and carried to the processor by two scooper-loaders (refs. 18–20). Ore is carried from the mining area on a conveyor system. At the launch area it is compacted to fit into a launcher bucket, and then fused.

The site for the base is in the Cayley area at 4° N. 15° E. where Apollo 16 landed. This site was selected because of richness of lunar ore, suitably flat terrain for the launcher, and the near-side equatorial region gives a suitable trajectory to L_2. Apollo samples had an aluminum content between 4.5 and 14.4 percent, the highest percentage being from this site. The Apollo missions did not provide any evidence of rich ore veins below the lunar surface.

Lunar bases have been the subject of many design studies (refs. 18–20). The total mass of housing and life support equipment is approximately 2000 t brought from Earth to accommodate the construction crew of 300 persons. During the mining operations, there are only 150 persons at the base of whom approximately 40 are support personnel. Consumables of 4.95 kg (including 0.45 kg for losses) per person-day are supplied from Earth. The mass imported each year is given in table 5-13. Almost all activities are in a "shirt sleeve" environment within the shielded structure. A large area is provided for repair work. The mass and power required for these operations on the Lunar Base are summarized in tables 5-14 and 5-15.

The Mass Launcher

Critical to the success of the entire system of colonization of space is the ability to launch large amounts of matter cheaply from the Moon. There are two aspects: launching the material from the Moon by an electromagnetic launcher using the principle of the linear induction motor, and gathering the lunar material in space by an active catcher located at L_2.

Each second the mass launcher accelerates five 10-kg masses of lunar material to lunar escape velocity of 2400 m/s. Errors in launch velocity are kept within 10^{-4} m/s along the flight path and 10^{-3} m/s crosswise to it.

The masses are carried in an accelerating container or "bucket." Built into the walls of each bucket are liquid-helium-cooled superconducting magnets which suspend it above the track. The buckets are accelerated at 30 g over 10 km by a linear electric motor running the length of the track. The bucket then enters a drift section of track, where vibrations and oscillations lose amplitude enough for the payload to be released with great precision of velocity. The velocity of each bucket is measured, and adjusted to achieve the correct value at release.

During acceleration the payload is tightly held in the bucket, but when lunar escape velocity is reached and the velocity is correct the payload is released. Since the bucket is constrained by the track to follow the curve of the lunar surface, the payload rises relative to the surface and proceeds into space. Each bucket then enters a 3 km region where a trackside linear synchronous motor decelerates it at over 100 g. It is returned to the loading end of the track along a track parallel to the accelerator.

At the load end of the track the liquid helium used to cool the superconducting magnets is replenished, and a new payload loaded. Then the bucket is steered to the start of the accelerator for another circuit. Figure 5-19 (overleaf) shows the mass launcher schematically. More details are given in appendix F.

With a 70 percent duty cycle, this system can launch 1.1 Mt/yr. To assure this duty cycle during lunar night as well as lunar day, two complete mass launchers are necessary. A nuclear power plant rather than a solar plant is required so the operation can continue through the lunar night.

TABLE 5-13.– ANNUAL MASS IMPORTS

Imports	Mass, t/yr
Crew consumables	270
Maintenance supplies	100
Crew rotation*	14
Atmosphere leak replacement	18
Total	402

*The same mass is also transported from Moon to Earth.

TABLE 5-14.– LUNAR BASE EARTH-SUPPLIED MASS

System	Mass, t
Mining and conveyor system	250
Housing and life support	2,400
Technical support	500
Launcher	4,000
Power plant (200MW + 10%)	9,900
Total	17,050

TABLE 5-15.– LUNAR BASE POWER REQUIREMENTS

System	Power, MW
Launcher	192
Mining	0.7
Compaction	7.15
Living quarters	.15
Total	200

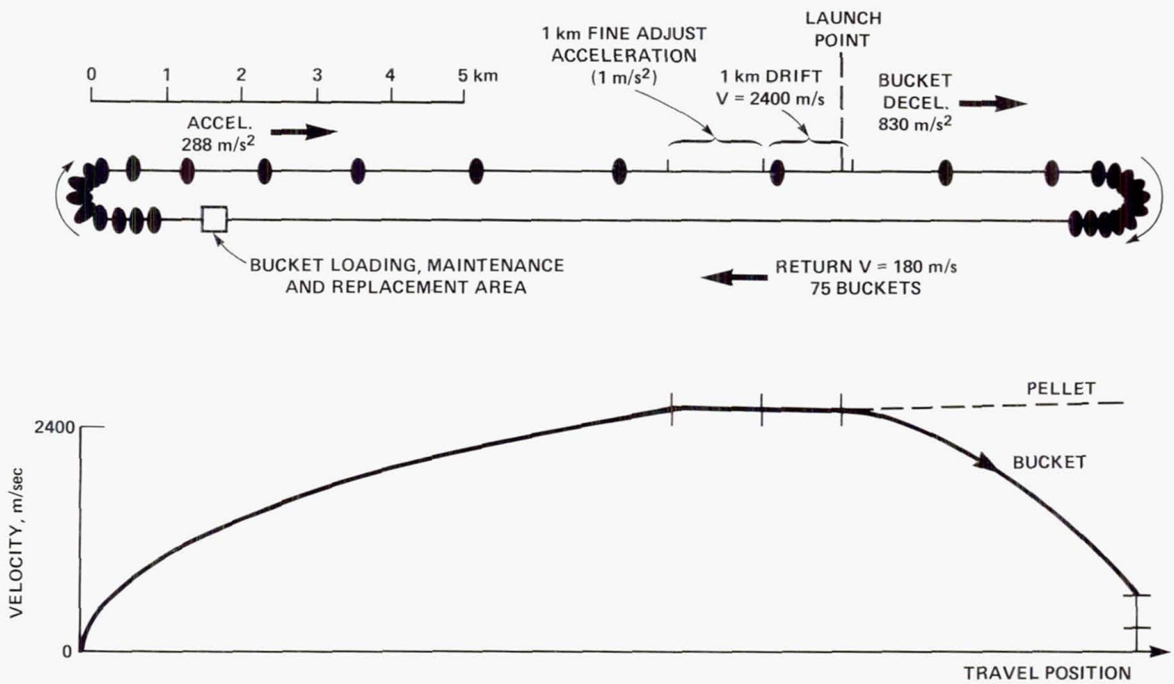


Figure 5-19.– *The mass launcher.*

Power and Supply

Several nuclear reactor single-cycle helium-Brayton plants of 10 to 50 MW each are used instead of a single big plant because the smaller plants can be transported assembled and become ready to operate by use of space shuttle main engines. The redundancy of several smaller systems is attractive, especially since the plants need to be taken off-line for refueling every year or two.

The total capacity is 220 MW and the total mass is 9900 t, including a 10 percent design factor.

The mass of the power plant is estimated using the value of 45 t/MW, which is projected to be applicable to nuclear plants within the decade.[1] Shielding will be provided by lunar material.

THE MASS CATCHER AT L_2

The problem of collecting the stream of material launched by the mass-driver is solved by a kind of automated "catcher's mitt," the mass catcher, located at L_2. Although the catchers are fully automated there is a 2-person space station at L_2 for maintenance personnel. This station is adequately shielded against possible hits by stray payloads.

Because it would be dangerous to navigate in the vicinity of the catcher while the launcher is operating, you are not able to visit the catcher personally. Instead you learn about it from an operator who is at the Moon base on recreation leave.

He tells you that the mass catcher is an active device to capture payloads of lunar material shot by the mass launcher. The payloads are solid blocks 0.20 m in diameter, made of compacted and sintered lunar soil. Each payload has a mass of 10 kg and arrives at L_2 with a speed of 200 m/s.

The catcher is in the form of a thin, light net, 10 m^2 in area, which is manipulated by three cables to position the net anywhere within an equilateral triangle. The cables are wound on reels which move on three closed loop tracks. Each side of the equilateral triangle is 1 km, thus providing a 0.43×10^6 m^2 catch area. The total mass of the catcher is 220 t.

[1] Austin, G., NASA-Marshall Space Flight Center, personal communication, June, 1975.

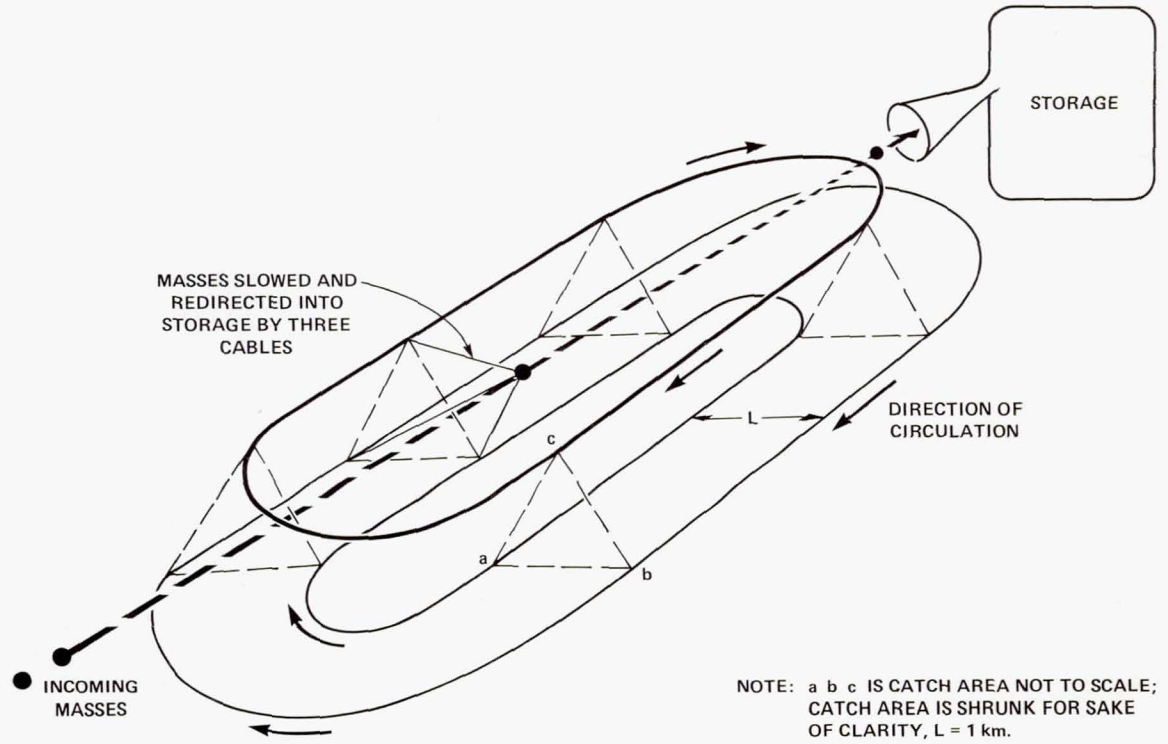


Figure 5-20.– *The mass catcher.*

Station-Keeping With the Rotary Pellet Launcher

You learn that the mass catcher uses an unusual propulsion device – a rotory pellet launcher – to position the catcher so that it is always facing the incoming stream of payloads. Furthermore, this device provides a counterthrust to the force of some 2000 N imparted to the catcher by the stream.

Further details of the mass catcher are provided in appendix G, and because of their importance the trajectories from the Moon to L_2 and their relation to station-keeping are described in appendix H. The mass catcher is illustrated in figure 5-20.

The rotary pellet launcher is a heavy tube rapidly rotating to accelerate and eject small pellets of rock. (See fig. 5-21.) Velocities as high as 4000 m/s may be attained, equal to the exhaust velocities of the best chemical rockets. The pellets themselves are sintered or cast directly from lunar rock, with no chemical processing required. The launcher uses 5 percent of the mass received as propellant. (For further analysis see appendix I.)

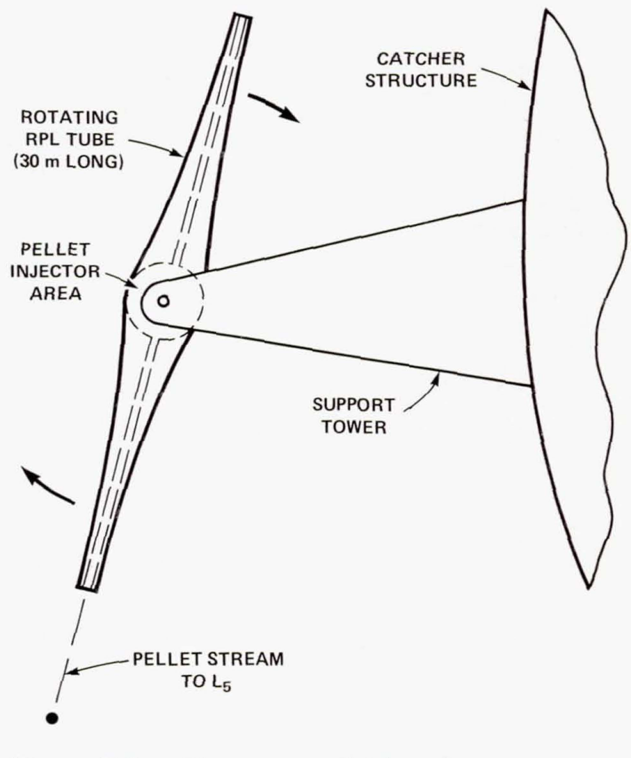


Figure 5-21.– *The rotary pellet launcher*

This rotary pellet launcher is mechanically driven by an onboard nuclear power system rated at 20 MW. The power plant radiator is situated in such a manner as to radiate freely to space while being shielded from impacts of stray masses. The inner surface of the radiator is insulated and made highly reflective, so as to avoid heating the catcher.

The transport of lunar material from the catcher to the colony is accomplished using a space ore-carrier. The trip from L_2 to L_5 requires some 2 months. The rotary pellet launcher is the primary propulsion system since a thrust of only several thousand newtons must be obtained over a period of weeks to perform the mission. Of course, the rotary launcher cannot be used in the vicinity of either the colony or the mass-catcher, because of the danger from its exhaust of high-velocity pellets. For low-velocity maneuvers in these vicinities chemical rockets can be used.

You express concern to the operator of the mass catcher over the possible hazard of using high velocity pellets as propellant mass because they constitute artificial meteoroids. They are ejected with high velocity, not so high as to escape the Solar System, but sufficiently high to escape the Earth-Moon system and take up solar orbits. Typically, they will range inward as far as Venus and outward to Mars' orbit.

The operator's response is reassuring. He reminds you that the astronomer George Wetherill (ref. 21) studied the lifetimes of meteoroids in such orbits, or the times before collision with Earth. He found a mean lifetime of 10^7 years. The Earth presents a surface area of 5×10^8 km^2, while a colony's area is some 1 km^2 or less, and a spacecraft's area much less. Using a standard that no more than one impact from a pellet per square kilometer every 10 yr may be allowed, then 5×10^{14} pellets may be permitted to orbit the Sun following ejection. If each has a mass of 10 g, the allowed mass of ejected pellets is 5×10^9 t. This is some 10,000 times the mass of pellets to be ejected in the course of carrying material for building the colony. He assures you that the rotary pellet launcher will be a useful propulsion system for many years, before the environmental effect of ejected pellets becomes noticeable in comparison to the effect of meteoroids naturally present in space.

HOME TO EARTH

It is now 2 months since you left Earth. In that time you have traveled over 750,000 km, you have another 386,000 to go to get home to Earth. You have seen a tiny community of 10,000 men and women crowded into the colony and in small bases on the Moon and at L_2 separated by vast distances which are in turn dwarfed by the immensities of space. Homesickness is inevitable. It is time to leave the realms of the colonists. Their tasks and their will to do them are enormous, and only those people can be colonists who have a large capacity to work hard and long when, as soon happens, tedium replaces the initial excitement. You speculate that it will be mostly their children and grandchildren who will master space. The great mass of mankind will remain in the cradle of Earth; only a few will go into space.

You are fortunate to get a berth in one of the ships that brings supplies to the Moon and rotates personnel from the Moon base directly back to Earth. In the early years all the men and women of the base went straight back to Earth and so the personnel transporter was full to capacity. Now increasing numbers choose to spend their rotation time at L_5 instead of on Earth and berths are available on the run to Earth. You wonder whether this seed of human society planted in such an unlikely environment will flourish, and settling back into your seat to read a terrestrial news magazine you conclude that only time will tell.

APPENDIX A

STRUCTURAL DESIGN CONCEPT FOR A SHELL STRUCTURE

A section from a symmetric structural shell transmitting only normal stresses in orthogonal directions may be designed either as a stressed skin or a rib system. The stressed skin is the most efficient in that the same material carries the stress in both directions and there is integral resistance to secondary torsional and bending loads. In addition, both fabrication and construction generally are simplified and problems with sealing joints, finishing, and maintenance are reduced.

For a rib system, such as shown in figure 5-22, each orthogonal set must entirely carry the membrane force (N_1 or N_2) in that direction. This increases the mass required to carry the membrane stresses by the factor $(\sigma_1 - \sigma_2)/\sigma_1$ (where $\sigma_1 > \sigma_2$ and σ_1 and σ_2 refer to the membrane stresses in directions 1 and 2) plus the intermediate plates required to bridge between the ribs. Moreover, if the ribs are made of cable and are flexible there is no resistance to secondary torsion, bending, or buckling. There may, however, be some advantages in fabrication and construction to include some cables encased in the ribs.

The obvious requirement for any shell configuration is to avoid ribs whenever possible. Therefore, this design assumes a stressed skin structure except in the windows where the required ribs flare into the skin at the boundaries.

Design Formulas for Torus

For a stressed skin design of a torus the required skin thickness in the meridional and hoop directions, respectively, are given by

$$t_m = \frac{p_o r}{\sigma_w} \tag{1}$$

$$t_h = \frac{(p_o/2)(r/R) + (p_g/\pi)}{\sigma_w - \rho R} R \tag{2}$$

where p_o = atmospheric pressure

p_g = equivalent pressure of pseudogravity

ρ = density of structural material

R = major radius

r = minor radius

σ_w = working stress

The analogous equations for the cylinder and sphere are

$$\text{Cylinder,}\ t = \frac{p_o + p_g}{\sigma_w - \rho R} R$$

$$\text{Sphere,}\ t = \frac{p_o/2 + p_g}{\sigma_w - \rho R} R$$

In general $t_h > t_m$ for the range of values of interest in this design. For the Stanford Torus, p_o = 51.7 kPa (7.5 lb/in.^{2}), R = 830 m, and r = 65 m. (Note: Since angular velocity must be ⩽ 1 rpm, then R + r ⩾ 895 m. Furthermore, projected area $4\pi Rr \geqslant 650{,}000$ m^2.) The structural material is assumed to be aluminum with ρ = 2.7 t/m^3 and σ_w = 200 MPa (29,000 lb/in.^{2}). The value used for p_g is 7.66 kPa (160 lb/ft^2), which is 530,000 t of internal mass on a projected area of 678,000 m^2. For a tabulation of internal mass, see tables 5-2 and 5-3.

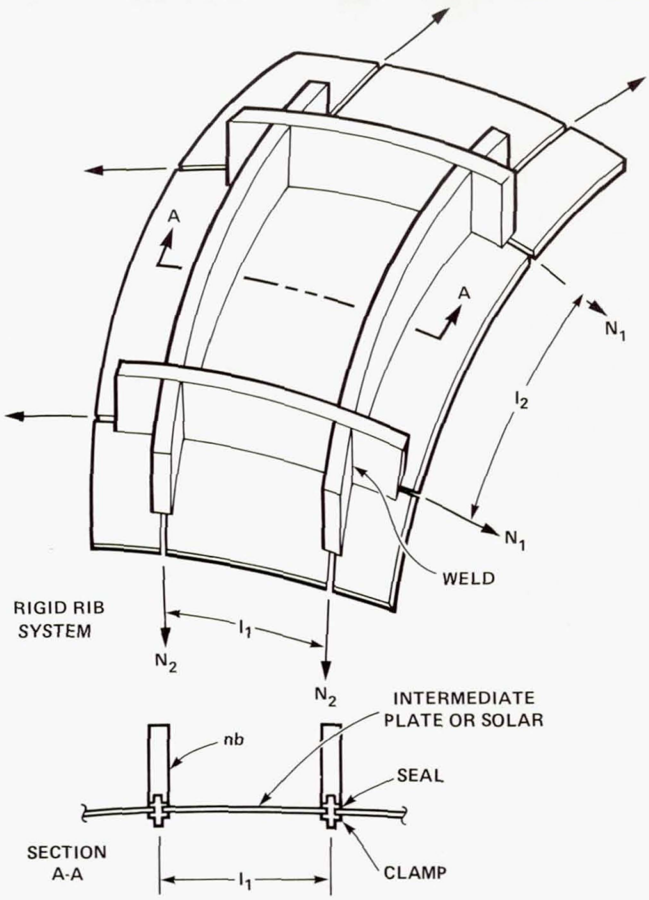


Figure 5-22.– *Shell structure rigid rib system.*

The thickness required to contain both atmospheric pressure and internal mass is determined by equation (2):

$$t_h = 2.08 \text{ cm}$$

Considering atmospheric pressure only, equation (1) governs:

$$t_m = 1.68 \text{ cm}$$

This represents a difference in cross-sectional area of $2\pi r(t_h - t_m)$ = 1.634 m^2. An efficient way to use the structural material might be to construct the shell with the minimum thickness needed to withstand the atmospheric pressure, and provide the additional required area in the form of hoops incorporated into the supporting substructure of the internal structures, as illustrated in figure 5-23 (overleaf).

The structural mass for a torus design with a stressed skin is determined by

$$M_{ss} = 4\pi^2 rRt_h = 120{,}000 \text{ t}$$

On the other hand, if a completely ribbed system were used the structural mass would be

$$M_{rib} = 4\pi^2 rR(t_m + t_h) = 229{,}000\ t$$

but t_h must now be determined by

$$t_h = \left[\frac{(p_o/2)(r/R) + (p_g/\pi)}{\sigma_w - \rho R}\right] R + t_m = 2.29\ \text{cm}$$

Since approximately 1/3 of the surface area consists of solars (the chevron windows), the mass of the standard torus is taken as 2/3 M_{ss} + 1/3 M_{rib}, which equals 156,000 t.

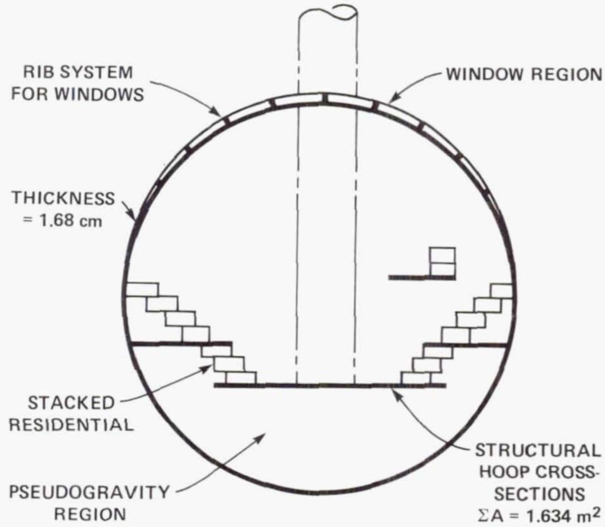


Figure 5-23.– *Torus structural cross section.*

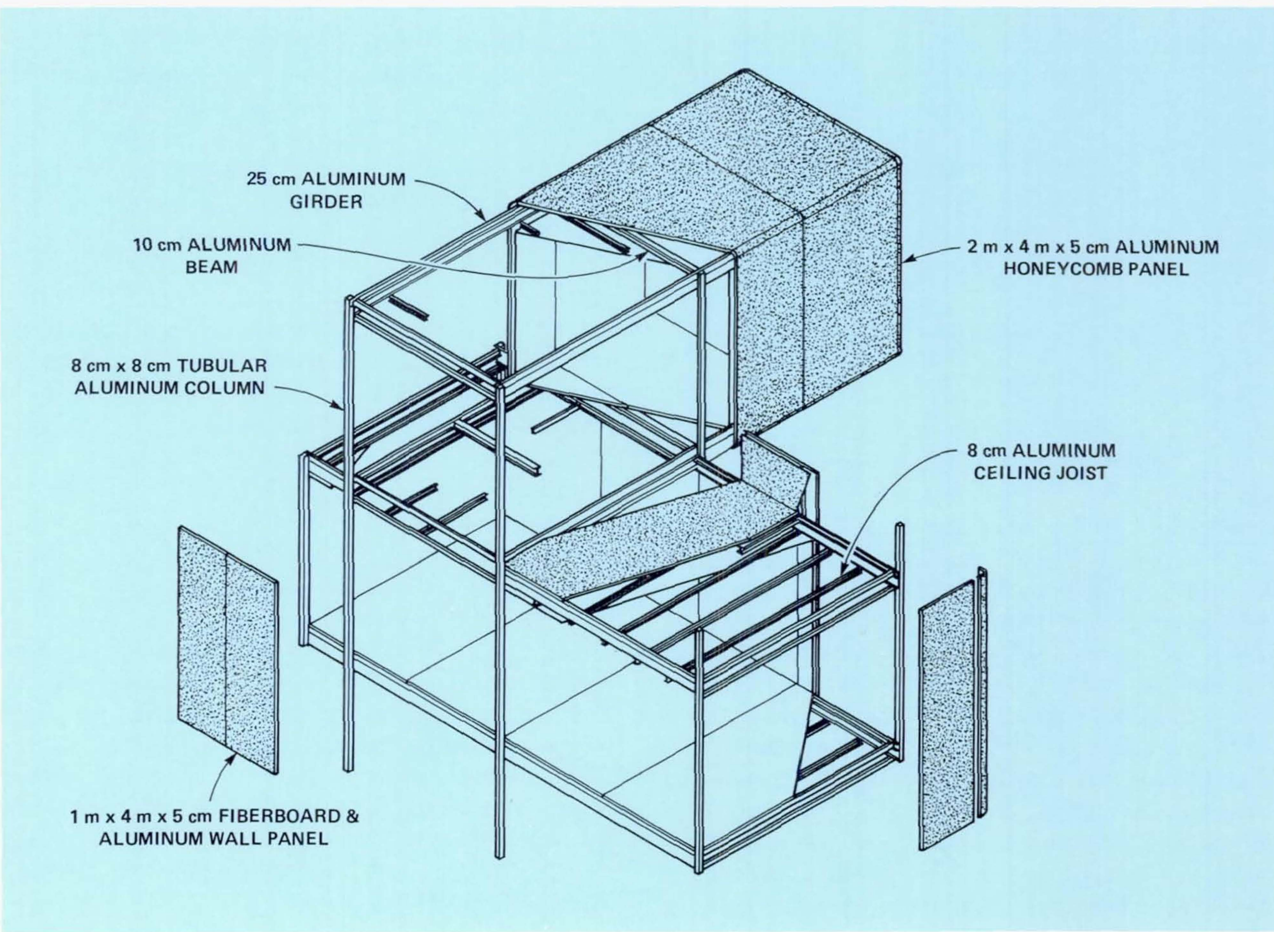


Figure 5-24.– *Structural frame assembly.*

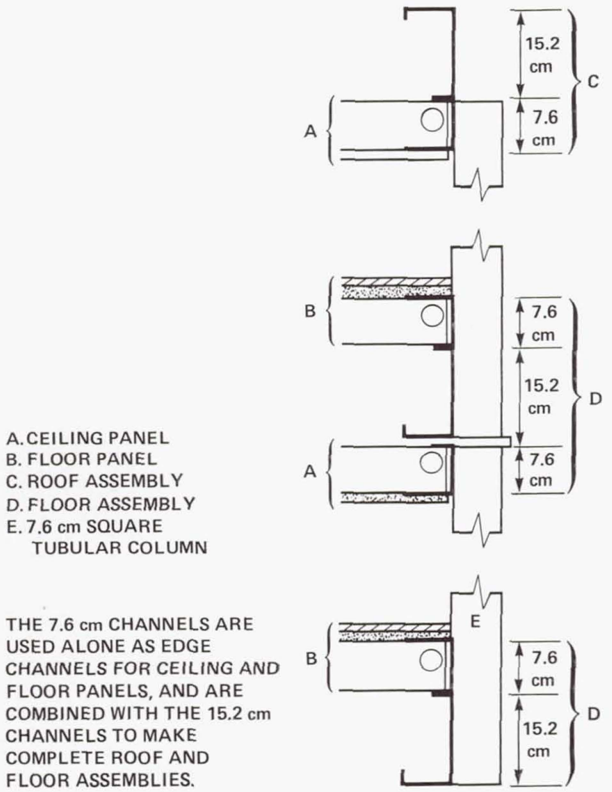


Figure 5-25.– *Column and beam connection detail.*

APPENDIX B

STRUCTURAL SYSTEM FOR HOUSING

The structural system consists of aluminum tube columns with a typical 4 × 6 m bay size. Beams are also aluminum, spaced at 2 m on center. Beams and columns have fixed connections to form rigid boxes, allowing them to span up to 6 m. Figure 5-24 shows this structural frame assembly and figure 5-25 details the beam and column connections.

Floor elements consist of 5-cm-thick aluminum honeycomb sandwich panel construction. Structural calculations for such a floor and beam system were developed for use in Skylab and as such have been assumed for use in the colony. The system allows dead load weights of less than 120 Pa (2.5 lb/ft^2) and is capable of taking upwards of 12 kPa (250 lb/ft^2) in live load (ref. 22). Walls could be a number of different materials. For sound isolation and for fire protection, a 10-cm-thick silicon cellular panel has been assumed. Ceiling construction, likewise a fire resistive construction, is also made from silicon fiberglass.

APPENDIX C

AGRICULTURE

The agricultural system is derived from standard nutritional requirements for adult men and women and for children. The space colony population is used to normalize these requirements to that of a "typical" person weighing 60 kg as shown in table 5-16. These requirements are met by an average daily diet which is shown in table 5-17(a) which also includes the caloric and nutritional values calculated for this diet. The nutritional requirements are met and an excess of protein is provided by a substantial margin. Vitamins and trace minerals are also available in excess quantities as shown in table 5-17(b). A more careful analysis of the colony's protein requirement could provide savings in meat requirements and, in turn, provide substantial savings in the required land area for plants.

The diet is treated as a daily average of all components as if each colonist ate a small portion of each foodstuff each day. In reality, of course, the colonists would eat a varied selection that over time averages to this diet. The individual components of the diet are chosen to provide adequate variety for both nutritional and psychological purposes. These components are meant to be representative of classes of foods and not specifically limited to these items. For example, pork could be considered as a feasible diet component with feed and area requirements intermediate between beef and rabbits. In addition, it should be explicitly stated that this diet represents typical American preferences and does not recognize ethnic or religious dietary preferences. It is reasonable to expect, however, that such preferences could be adopted if desired.

TABLE 5-16.– HUMAN NUTRITIONAL REQUIREMENTS

	Body weight, kg	Colony population	Daily requirement per person (ref. 1)	
			Calories	Protein, g
Adult men	70	4853	2900	70*
Adult women	58	4633	2100	58*
Children**	32	864	2150	54
Weighted average	61		2479	63.3

*Colony workers may require higher protein intake due to strenuous workloads.

**Assumes a normal age and sex distribution of children under 18 years old.

The meat in this diet dictates the requirement for a stable herd of animals for which the rates of birth and slaughter are equal. In effect, each colonist has 26 fish, 6.2 chickens, 2.8 rabbits and about 1/7 of a cow (see table 5-5). The plant diet for these animals plus that for humans then forms a total requirement for all plants as given in table 5-18. Food processing byproducts and silage are extensively used in satisfying the animal diet. Implicit in this derivation is allowance for yields in meat dressing and food processing, for moisture and silage content of the grains, and for the metabolic requirements of the various animals. These factors are given in table 5-19, parts A–J, along with the carbon, nitrogen, hydrogen, and oxygen elemental balance for each step in the food chain (refer to fig. 5-16). Sorghum is chosen as a principal component of the animal diet because it can be produced in excellent yield and because it provides a source of protein (11 percent) while also providing silage and sugar. Protein make-up for the animal diet is provided from soybean (34 percent) and from meat processing byproducts.

From the quantitative requirements for each plant component, total plant growing area requirements can be obtained based upon estimates of crop yields as presented in table 5-4.

The success of the colony's agricultural systems rests entirely upon the photosynthetic productivity. Crops were estimated assuming a yield double that of the world record for that crop, as shown in table 5-20. In addition, a factor of 1.1 improvement is obtained by shortening the growing season from 100 to 90 days. The record yield data come from harvests under good but not ideal or controlled growing conditions. Comparison of typical terrestrial and space colony growing conditions is presented in table 5-21. Including the shortened season, the net improvement is a factor of 2.2 which is further enhanced by harvesting 4 crops per year. Thus the farmer in a typical American midwestern farm who produces 100 bushels of corn per acre in a single season year would look with astonishment on the space colony farmer who produces 4164 bushels of corn from a single acre in his 4-season year. While this factor of 40 is substantial, it is believed to be credible since a portion of it is derived from year-round growing. Substantiation of crop yields is required and can be obtained through careful study under controlled conditions (and most of the research could be performed on Earth). The improvement that has already been achieved for certain vegetables in Abu Dhabi (ref. 5) is shown in table 5-22.

The summer study did not pursue the issue of food reserves, design margins and safety factors with respect to agriculture. Due to the importance and fragility of the agricultural system further study should consider this issue. In general, it was felt desirable to produce some excess food continuously, store some of the excess as reserve, and recycle the remainder. In fact, it would seem wise to design the system such that the colony could survive on the output of two of the three agricultural units for a period of several months if some disaster ruined production in one of the areas. Also, the study did not pursue microbial and insect ecology but did assume that these important areas could be resolved upon further study.

TABLE 5-17.– (a) AVERAGE DAILY SPACE COLONY DIET (g/PERSON)

Source	Amt, g	Calories, kcal	Carbo-hydrates, g	Fats, g	Protein, g
Meat					
Trout	40	78	0	4.6	8.6
Rabbit	40	64	0	3.2	8.4
Beef	40	142	0	12.8	6.3
Chicken	40	49	0	1.3	8.8
Produce					
Eggs	24	39	0.2	2.8	3.1
Milk	500	330	24.5	19.0	17.5
Dry plant produce					
Wheat	180	608	130.1	3.6	24.3
Rice	100	363	80.4	.4	6.7
Sugar	100	385	99.5	0	0
Vegetables and fruit					
Carrots	100	42	9.7	0.2	1.1
Lettuce	100	14	2.5	.2	1.2
Peas	150	126	21.6	.6	9.5
Apple	100	56	14.1	.6	.2
Potato	100	76	17.1	.1	2.1
Tomato	100	22	4.7	.2	1.1
Orange	100	51	12.7	.1	1.3
Totals	1814	2445	417.1	49.7	100.2

Note: Calculated from reference 2.

TABLE 5-17.– (b) VITAMIN AND MINERAL COMPOSITION OF AVERAGE DIET

Nutrient	Space Colony average diet*	Recommended daily allowances**
Vitamin A (iu)	14,399	4915
Vitamin C (mg)	144	56
Niacin (mg equiv)	33	15
Riboflavin (mg)	2.1	1.6
Thiamin (mg)	2.2	1.2
Calcium (g)	0.88	0.82
Phosphorus (g)	1.57	0.82
Iron (mg)	17.0	13.6
Potassium (mg)	3,549	Not listed
Sodium (mg)	1,680	Not listed
Linoleic acid (g)	1	Not listed
Cholesterol (mg)	319	Not listed

*Average diet evaluated in cooked form.
Source: Watt, B. K., and Merrill, A. L. Composition of Food. Agriculture Handbook, No. 8, USDA, Washington, D. C. Revised 1963.

**Each value is weighted to reflect the population composition of 8 percent children (weighing 28 kg), 47 percent adult males (70 kg), and 45 percent adult females (58 kg).
Source: Recommended Dietary Allowances, 7th edition, National Academy of Sciences, 1968.

TABLE 5-18.– TOTAL PLANT REQUIREMENTS, g/PERSON/DAY

	Sorghum*	Soybean*	Wheat*	Rice*	Corn*	Fruits and vegetables	Other	Totals
Man			225	125		937	125[a]	1412
Cattle	217	100					633[b]	1470
Chickens		170			30		37[c]	
Rabbits	100	100			20			
Fish		100					81[d]	
Totals	317	470	225	125	50	937	758	2882

Notes:

*Dried grain.

[a]Man also utilizes 125 g/person/day of sugar extracted from sorghum.

[b]Cattle also utilize 633 g/person/day roughage from sorghum and soybean.

[c]Chickens also utilize 37 g/person/day fish meal.

[d]Fish also utilize 81 g/person/day animal meal from meat processing byproducts.

(c and d are not included in totals)

TABLE 5-19.– FACTORS OF METABOLIC REQUIREMENTS

A. Diet requirements for man (from table 5-17(a)), g/day

	Total	C	H	O	N
Meat					
Trout	40	7.6	4.2	27.0	1.2
Rabbit	40	6.4	4.2	28.2	1.2
Beef	40	12.8	4.4	21.9	.9
Chicken	40	5.3	4.2	29.3	1.2
$\sum$	160	32.1	17.0	106.4	4.5
Produce					
Egg	24	3.7	2.6	17.3	.4
Milk	500	32.5	54.0	411.0	2.5
$\sum$	524	36.2	56.6	428.3	2.9
Dry plant products					
Wheat	180	67.5	13.9	95.2	3.4
Rice	100	35.8	7.6	55.7	.9
Sugar	100	40.0	7.0	53.0	---
$\sum$	380	143.3	28.5	203.9	4.3
Vegetables, fruit					
Carrot	100	4.6	10.6	84.6	.2
Lettuce	100	1.7	10.9	87.2	.2
Pea	150	13.6	15.3	119.7	1.4
Apple	100	6.2	10.4	83.3	.1
Potato	100	8.0	10.2	81.4	.3
Tomato	100	2.5	10.8	86.5	.3
Orange	100	5.8	10.5	83.5	.2
$\sum$	750	42.4	78.7	626.2	2.7
Total food intake					
$\sum$ above	1814	254	181	1365	14
H_2O	750		83	667	
$\sum$	2564	254	264	2032	14

C/H/O/N ratios for food calculated from data of reference 2.

TABLE 5-19.– CONTINUED.

B. Mass balance on person

	Total	C	H	O	N
In					
Food	2564	254	264	2032	14
O_2	686			686	
H_2O	400		44	356	
Out					
CO_2	857	231		626	
H_2O	857		94	763	
Wastes	1936	23	214	1685	14

C. Mass balance on food processing

	Total	C	H	O	N
In					
Meat and produce	724	84	77	556	7
Plant	1412	233	134	1037	8
H_2O	750		83	667	
Out					
Food	2564	254	264	2032	14
Kitchen waste	322	63	30	228	1

Based on: 20% of meat and plant materials are lost to waste.

D. Mass balance on animal harvesting

	Total	C	H	O	N
In					
Meat and produce	1168	138	126	890	14
Out					
To nonhuman	444	54	49	334	7
To food processing	724	84	77	556	7

Based on: 33% of milk to nonhuman food processing
Efficiencies of meat harvest (dressed/animal)

fish	35%
steers	55%
rabbits	65%
chickens	60%

TABLE 5-19.– CONTINUED.

E. Mass balance on nonhuman food processing – Animal

	Total	C	H	O	N
In					
Fish	93	18	10	62	3
Beef	41	13	5	22	1
Chicken	33	4	4	24	1
Rabbit	27	3	3	20	1
Milk	250	16	27	206	1
Out					
Meal	118	54	13	44	7
H_2O	326		36	290	

Based on: Animal meal has 15% moisture.

F. Mass balance on animals

	Total	C	H	O	N
In					
H_2O	3853		424	3429	
Nonhuman veg	1470	575	121	736	38
Meal	118	54	13	44	7
O_2	747			747	
Out					
H_2O	1494		164	1330	
CO_2	939	254		685	
Meat, milk, eggs	1168	138	126	890	14
Waste	2587	237	268	2051	31

TABLE 5-19.– CONTINUED.

F.1. Animal food requirements

Beef steer: 1 steer for 11 persons
- Harvested at 400 kg after 16 months
- Metabolic requirements for 1/11 250 kg steer
  - 300 g sorghum mix/day
  - 200 g soybean mix/day

Roasting chicken: 5.6 chickens/person
- Harvested at 2.6 kg after 25 weeks
- Metabolic requirements for 5.6 chickens at 1.1 kg each
  - 37 g fish meal/day
  - 150 g soybeans/day

Rabbits
- Harvested at 3.4 kg after 125 days
- Metabolic requirements for 2.8 rabbits at 1.8 kg each
  - 100 g sorghum/day
  - 100 g soybean/day
  - 20 g corn/day

Dairy cattle
- 400 kg cow produces 12.45 kg milk/day
- Metabolic requirements for 1/16.6 cow at 400 kg
  - 350 g sorghum mix/day
  - 100 g soybean mix/day

Laying hens
- 1.5 kg hen lays 5 eggs/week, 54 g/egg
- Metabolic requirements for 6/10 hen at 1.5 kg
  - 20 g soybeans/day
  - 30 g corn/day

Fish
- Harvested at 2 kg in 1 yr
- Metabolic requirements for 26 fish at 1 kg each
  - 100 g soybean/day
  - 81 g animal meal/day

Summary

Plant matter	Total	C	H	O	N
Beef steer	500	187	40	263	10
Roasting chicken	150	67	13	62	8
Rabbits	220	89	19	105	7
Dairy cow	450	167	36	240	7
Laying hen	50	20	4	25	1
Fish	100	45	9	41	5
Total	1470	575	121	736	38
Animal meal					
Roasting chicken	37	17	4	13	3
Fish	81	37	9	31	4
Total	118	54	13	44	7

TABLE 5-19.– CONTINUED.

F.2. Animal metabolic requirements, g/day
[Based on animal biomass of F.1. above.]

	In		Out			
Animal	O_2	H_2O	CO_2	H_2O	Meat produce	Waste
Beef steer	180	910	230	450	91	819
Roasting chicken	168	616	210	146	83	532
Rabbit	88	302	110	189	77	235
Dairy cow	220	1840	275	690	750	795
Laying hen	23	85	29	19	24	86
Fish	68	100	85	---	143	121
Total	747	3853	939	1494	1168	2588

Data based on following:

Food requirements (ref. 22)

For caloric and nitrogen requirements – diets calculated

Metabolism (ref. 22)

CO_2 calculated by $O_2/0.8$

Chicken egg production (ref. 23)

Fish Food and metabolism; personal communication, Chris. Brittelson, Wisconsin Dept. of Natural Resources, Nevin Fish Hatchery, Madison, Wisconsin.

G. Mass balance on non-human food processing – Plant

	Total	C	H	O	N
In					
Sorghum	1406	119	144	1138	5
Sorghum roughage	1829	152	188	1485	4
Soybean	2103	211	222	1646	24
Soybean hay	883	75	91	713	4
Corn	220	18	23	178	1
Total	6441	575	668	5160	38
Out					
To animals	1470	575	121	736	38
Water	4971		547	4424	

Based on: Sorghum roughage 14.5% moisture after drying
Soybean hay 10.8% moisture after drying
Two times dry roughage or hay as seed

TABLE 5-19.– CONTINUED.

H. Mass balance on plant harvest

	Total	C	H	O	N
In					
From fields	16,273	1347	1682	13,172	72
Out					
To food processing	1,412	233	134	1,037	8
To nonhuman food	6,441	575	668	5,160	38
H_2O	1,205		133	1,072	
Waste	7,215	539	747	5,903	26

H.1. Plants from field

Material	Total	C	H	O	N
Sorghum	4080	341	419	3309	11
Soybean	4620	425	481	3678	36
Corn	1034	86	107	838	3
Wheat	3018	254	309	2442	13
Rice	1647	135	168	1341	3
Fruits and vegetables	1874	106	198	1564	6
Total	16,273	1,347	1,682	13,172	72

H.2. To food processing

Material	Total	C	H	O	N
Wheat	225	85	17	119	4
Rice	125	45	9	70	1
Vegetables	937	53	99	782	3
Sugar	125	50	9	66	---
Total	1412	233	134	1037	8

TABLE 5-19.– CONTINUED

H.3. Drying human food – wheat materials balance

Material	Total	C	H	O	N
In					
From field	3018	254	309	2442	13
Out					
To food processing	225	85	17	119	4
H_2O	781		86	695	
Waste	2012	169	206	1628	9

Based on: 1/3 dry weight is grain
Harvested at 80% moisture

H.4. Drying human food – rice materials balance

Material	Total	C	H	O	N
In					
From field	1647	135	168	1341	3
Out					
To food processing	125	45	9	70	1
H_2O	424		47	377	
Waste	1098	90	112	894	2

Based on: 1/3 dry weight is grain
Harvested at 80% moisture

H.5. Harvest waste

Material	Total	C	H	O	N
Fruit and vegetable	937	53	99	782	3
Sorghum roughage	845	70	87	686	2
Soybean roughage	1634	139	168	1319	8
Corn roughage	814	68	84	660	2
Wheat roughage	2012	169	206	1628	9
Rice roughage	1098	90	112	894	2
Total	7340	589	756	5969	26
Less sugar extracted from sorghum	125	50	9	66	---
Harvest waste	7215	539	747	5903	26

Based on: Soybean and grain roughage 80% moisture
Fruit and vegetable waste 50% of harvest and same composition
Corn is 1/5 of dry corn plant

TABLE 5-19.– CONCLUDED.

I. Mass balance on plants

	Total	C	H	O	N
In					
Irrigation water	168,750		18,563	150,187	
Recycle water	61,250		6,737	54,513	
Nutrients	93		21		72
CO_2	235,082	1347		3,642	
Out					
Plants	16,273	1347	1,682	13,172	72
Irrigation return	50,000		5,500	44,500	
Evapotranspiration	164,900		18,139	146,761	
O_2	3,909			3,909	

Based on: 30.5 cm water on 45 m^2 in 60-day season
50,000 g irrigation return

J. Mass balance waste processing

	Total	C	H	O	N
In					
Wastes	62,060	862	6759	54,367	72
O_2	2,476			2,476	
Out					
CO_2	3,193	862		2,331	
NH_4	93		21		72
H_2O	61,250		6738	54,512	

TABLE 5.20.– CROP YIELDS

			Terrestrial yields		Colony yields		
Crop	Record yield	Reference	g/m^2/season	Season, day	g/m^2/season	Season, day	g/m^2/day
Wheat	14 tons/ha	24	1400	100	2800	90	31
Rice	266 bu/ha	25	1596	100	3192	90	35
Soybean	9000 kg/ha	26	900	100	1800	90	20
Corn	26,500 kg/ha	25	2650	100	5300	90	58
Sorghum	675 bu/acre	25	3780	100	7560	90	83
Tomatoes	67 tons/ha	5	6700	~70	9240	70 as vegetables	132
Lettuce	24 tons/ha	5	2400	~70			

Unit weights

Rice	60 lb/bu
Sorghum	56 lb/bu
Soybean	60 lb/bu
Corn	56 lb/bu

Conversion factors

1 ha = 100 × 100 = 10^4 m^2

1 kg/ha ≅ 1 lb/acre

1 bu = 35.24 liters

1 ton = 0.906 tonnes (t)

TABLE 5-21.– PHOTOSYNTHETIC PRODUCTIVITY ENHANCEMENT

Factor	Terrestrial	Space Colony
Light intensity	Reduced by atmosphere and clouds	Greater by 7.5
Photo period	~12 hr	Can be 24 hr
pCO_2	17 Pa (0.13 mm Hg)	400 Pa (3 mm Hg) greater in growing area
Water	Sometimes dependent on rainfall	Irrigated regularly
Temperature	No control	Optimized for species
Season	1 per year in many areas	4 per year
Crop damage		
from weather	Hail, rain, wind	None
from pests and insects	5–15 percent loss of crop	None*
from weeds	2.5 to 5 percent loss of crop	None*
from disease	10 to 60 percent loss of yield	None*

*Controlled by quarantine.

TABLE 5-22.– INCREASED PRODUCTIVITY FACTORS* IN VEGETABLES (ref. 24)

Cabbage	2.59
Cucumber	8.48
Eggplant	12.63
Lettuce	2.33
Okra	4.73
Tomato	2.37
Turnip	7.14

*Under greenhouse conditions.

APPENDIX D

PRODUCTIVITY

Cost engineers in industry use a very simple model based on factors of man-hours of labor per unit of production. The factors are based on experience. The use of predetermined time and motion studies requires a finished engineering design and a methods study.

Let

e = man-hours per unit of the process, p, being performed, in Earth environment

F = factor by which e will be increased or decreased for the process, as a function of location

p = manufacturing, extracting, or erecting process being evaluated

W = quantity of the end product in production units

l = location at which the process will be carried out

E_p = man-hours required to produce W units of production by the process, p

E = man-hours required for some finished structure or unit.

Then for any process and any location,

$$E_p = WeF$$

and for any finished structure or unit,

$$E = \sum E_p$$

The model makes possible a labor estimate at any stage of design, simply becoming more detailed as to operations and factors as the design becomes more firm.

APPENDIX E

MASS SHIELDING

There are three mechanisms that are important in mass shielding. First, a charged particle excites electrons for many hundreds of angstroms about its trajectory. This excitation extracts kinetic energy at a roughly constant rate for relativistic particles and acts as a braking mechanism. For relativistic protons in low-Z matter this "linear energy transfer" is 2 MeV/g-cm^{-2} of matter. If the thickness of the mass shield is great enough a particle of finite kinetic energy is stopped. This is the least effective shielding mechanism in matter for relativistic particles.

The second mechanism is nuclear attenuation. For silicon dioxide the average nuclear cross section is 0.4 barn (10^{-24} cm^2). Thus if a charged particle traverses far enough in the shield (composed of silicon dioxide) it collides with a nucleus and loses energy by inelastic collisions with the nuclear matter. The measure of how far a particle must travel to have a substantial chance of nuclear collision is the mean free path, which for silicon dioxide is 106 g/cm^2. This mechanism is an exponential damper of primary beam particles.

Opposing the beam clearing tendency of nuclear attenuation is the creation of energetic secondary particles. For each nuclear collision there is beam loss from nuclear excitation, and beam enhancement (though with overall energy degradation through the increase of entropy) from the secondaries emitted by the excited nuclei. These secondary particles are, of course, attenuated themselves by further nuclear collisions with roughly the same mean free path as the primary particles.

The calculation of a mass shield can only be properly done by Monte Carlo simulation of the various pathways that the interactions can take. Two approximations often used either assume that secondary particles supplement nuclear attenuation well enough that only electron excitation stops the beam (the "ionization" approximation); or that secondary particle creation is negligible, resulting in beam attenuation by both nuclear attenuation and electron excitation ("ionization + exponential" approximation). Figure 5-26 plots the exposure rate versus all three formulations of shielding effectiveness for a cosmic ray spectrum incident on a copper shield. As the shield thickness becomes greater than approximately one mean free path length (for nuclear attenuation) the Monte Carlo result begins to show behavior that parallels the slope of the ionization + exponential approximation. The remaining difference is that the Monte Carlo result is a scale multiple of the ionization + exponential curve. This behavior then provides the following new approximation:

$$F = 5N_o\, e^{-x/l}$$

F = exposure rate,

N_o = initial exposure rate of primary beam,

l = mean free path for nuclear collision,

x = distance (g/cm^2) of shield traversed.

Since the secondary particle production factor for a high-Z nucleus like copper is greater than for low-Z nuclei this approximation should be conservative using the factor of 5 for secondary production. Because thick shields ($\gg 1$) are being considered, this equation's sensitivity to error is greatest in the value of l used, which fortunately can be accurately determined (106 g/cm^2 for silicon dioxide).

To calculate doses behind a shield the result is used that 1-rad in carbon is liberated by 3×10^7 cm^{-2} minimally ionizing, singly-charged particles. Within a factor of 2 this is valid for all materials. Assuming a quality factor of unity for protons, and an omnidirectional flux of protons at 3/cm^2-sec (highest value during the solar cycle) the dose formula is

$$\text{dose} = (16\ \text{rem/yr})e^{-x/106}$$

x = shield thickness (g/cm^2).

This is a conservative formula good to perhaps a factor of 2 in the thick shield regime. A spherical shell shield is assumed with human occupancy at the sphere's center. If the dose to be received is set at 0.25 rem/yr, to be conservative with the factor of 2, a required thickness of Moon dust (silicon dioxide) of 441 g/cm^2 is derived to protect the habitat.

As a final point, note that an actual shield will generally not have spherical symmetry. To handle this case the shield geometry must be subdivided into solid angle sections which, due to slant angles, have differing effective thicknesses. Equation (3) then has to be integrated over all the solid angle sections to calculate the received dose.

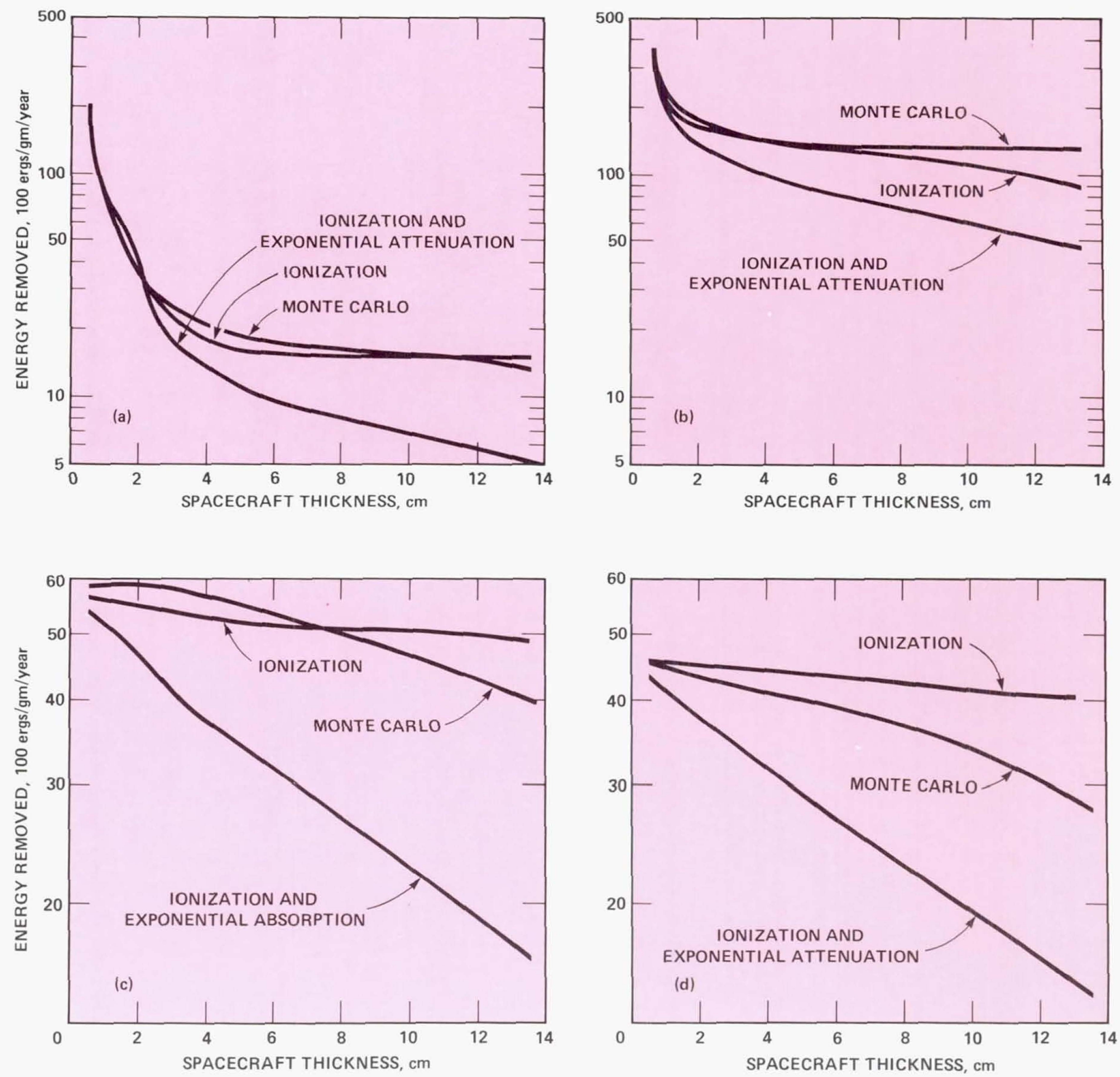


Figure 5-26.– *Cosmic ray exposure for different approximations for a copper shield as a function of thickness. (a) Solar maximum, thin tissue (ρ = 0.21); (b) Solar maximum, thick tissue (ρ = 1.0); (c) Solar minimum, thin tissue (ρ = 0.21); (d) Solar minimum, thick tissue (ρ = 1.0).*

APPENDIX F

THE MASS DRIVER

The baseline lunar material transportation system involves a magnetically levitated vehicle, or "bucket," accelerated by a linear synchronous motor. Acceleration is at 288 m/s^2 along 10 km of track. The bucket is accelerated through use of superconducting magnets at 3T; bucket mass is under 10 kg.

The suspension and control of motion required to implement the launch with a velocity error under 10^{-3} m/s are accomplished by a passive control system. The bucket and suspension are shown schematically in figure 5-27. The suspension involves paired magnetic coils, coupled mechanically to the bucket through an attachment which provides elastic suspension and damping by an energy-attenuating block made of a rubber-like material.

Figure 5-28 shows the frequency response of this system due to excitation. At 2400 m/s the range of misalignment wavelengths of 24 to 240 m gives the most severe response. Within that wavelength range misalignments cannot exceed 0.01 cm for the induced velocity not to exceed 10^{-3} m/s. At longer and at shorter wavelengths, more severe misalignments can be tolerated; for example, up to 0.1 cm at 2400 m.

Electromagnetic "bumpiness" deserves attention. This occurs with a wavelength of approximately 1 m, that is at 2400 Hz, due to use of discrete segments of accelerating coils on the linear synchronous motor. The maximum acceleration is proportional to the maximum angle of the bucket; if the bucket pitches down by 0.01 rad, the acceleration normal to the track is 3 m/s^2. The resulting velocity normal to the track is of amplitude 1.25×10^{-3} m/s. A tight suspension, incapable of sustaining large angular deflections in the bucket, reduces the bumpiness-induced oscillations to within desired limits. During a phase of drift, or of electromagnetic acceleration at low levels, the bumpiness may be reduced by orders of magnitude. Track misalignment and distortions, rather than electromagnetic bumpiness, are the major source of residual velocity error.

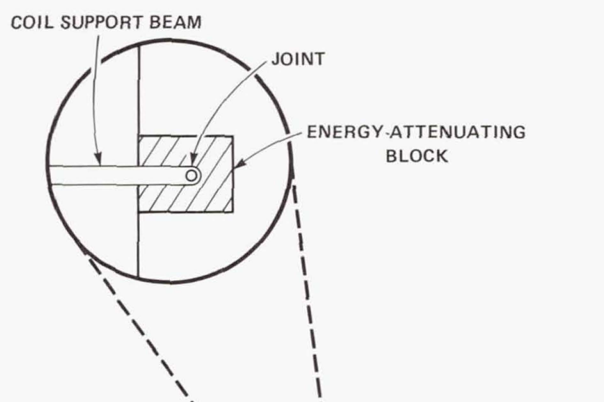


Figure 5-27.– *Track and suspension in cross section.*

Track Alignment

Three methods of track alignment might be considered.

1. Optical reticles viewed with a telescope. If the instrument is diffraction-limited at 1-m aperture, resolution is 10^{-6} rad, or 10^{-3} m at a distance of 1 km. By elevating reticles to account for lunar surface curvature the track may be initially aligned along the lunar surface.

2. Accelerometry. A bucket may be instrumented with recording accelerometers and made to traverse the track by coasting at high velocity, for example, 10^3 m/s, without acceleration. Track misalignments thus show up with high resolution.

3. Zone-plate alignment. This is the system used in the LINAC at the Stanford Linear Accelerator. Fresnel zone plates are used to focus a laser beam to a point; photodetectors locate the point and scan across it. The derivative of the luminous intensity across the point is found automatically and used to define reproducibly the center of the point, to an accuracy of 25 μm.

Launch Sequence

The launch sequence as a bucket proceeds along the track might be described as follows:

1. Coarse acceleration – 10 km at 288 m/s^2. The track may be coarse-aligned since larger oscillations are permitted than are tolerable prior to release. The velocity is measured along the track in real time using laser

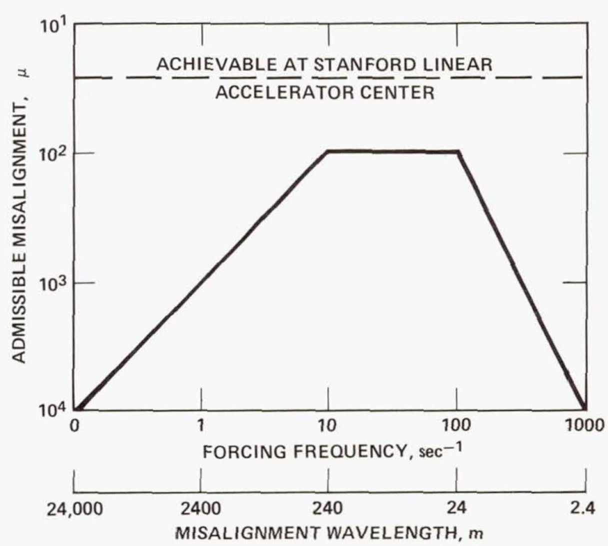


Figure 5-28.– *Admissible misalignment to cause velocity error of 10^{-3} m/s.*

doppler; an integration time of 5×10^{-5} s gives velocity accurate to 2×10^{-2} m/s. In this time the velocity change due to acceleration is 1.5×10^{-2} m/s so that velocity at cutoff of the acceleration may be made accurate to better than 3×10^{-2} m/s.

2. Fine acceleration – 1 km at 1 m/s^2. The track must be fine-aligned. Laser doppler integration time is 10^{-3} s; accuracy is 10^{-3} m/s; velocity change in this time is 10^{-3} m/s. The velocity cutoff is accurate to approximately this value, biased slightly above the desired velocity.

3. Drift – 1 km with deceleration due to electromagnetic drag, which may be below 10^{-2} m/s^2. The track is again fine-aligned. Laser doppler integration time is 10^{-2} s; accuracy is 10^{-4} m/s; velocity change in this time is below 10^{-4} m/s. A tradeoff exists between errors in launch velocity and errors in launch location; the launch is the event of payload release. This release occurs at a location calculated on the basis of the tradeoff, using the measured velocity.

4. Deceleration of bucket and return to loading zone. The deceleration may involve regenerative braking, to recapture (at least in part) the energy input into the bucket.

Payload Restraint System

The payload may be of sintered lunar material, resembling a cinder block. This block is rigidly held in place by trapezoidal restraints fitted to the sides of the block. These restraints are pin-secured and spring-loaded; pulling the pins causes the restraints to spring back. A final restraint, however, continues to press down on the block from above; this restraint may function as a mechanical "finger." This holds the block down during the fine acceleration and drift phases.

The track may be contoured to the lunar curvature, so that the block feels an upward acceleration, at escape velocity, of one lunar gravity (1.5 m/s^2). Thus, when the restraint is rapidly pulled away, the block drifts free. There is a spring effect due to the block having been compressed slightly by the restraint, with strain energy being stored in the block and converted to kinetic energy upon release. This effect leads to velocity errors at release of less than 10^{-5} m/s.

Track

The track cross section is shown in figure 5-27. This geometry was selected purely because it is convenient for a typical bucket; it is a conservative design in that a section of equal mass can be given greater stiffness. The section is of aluminum: density $\rho = 2.7$ g/cm^3, modulus of elasticity $E = 7 \times 10^{11}$ dynes/cm^2, and moment of inertia $I = 40{,}350\ t\ \text{cm}^4$ for t = thickness in cm.

The track is laid on supports in such a manner that the sag under its own weight, between the supports, is under 10^{-2} cm. At the supports, optical measurement equipment together with screw jacks permit accurate alignment of a straight track. The sag is given by the formula for sag (y_s) of a uniformly-loaded beam with ends clamped or built-in, a condition which is met by the beam being horizontal at the supports. This formula is

$$y_s = \frac{WL^4}{384\ EI}$$

where L = distance between supports, W = weight per unit length = (540 t g/cm) $\times$ (150 cm/s^2) = 0.81 N/m of length. Then, with $L = 10^3$ cm = 10 m, $y_s = 7.5 \times 10^{-3}$ cm. This is well within the misalignment permitted by figure 5-28.

The bucket has negative weight (since it is travelling at lunar escape velocity) and hence causes the beam to bend upward. The bucket has mass, say, of 30 kg; its weight is approximately 50 N. The resulting maximum static deflection (y_L) is:

$$y_L = \frac{PL^3}{192EI} = 1.8 \times 10^{-3}\ \text{cm}$$

for t = 0.5 cm. A design with t = 0.5 cm appears to offer adequate strength and rigidity.

The track mass is 27 kg/m of length. If shipped in lengths of 30 m, 167 lengths (5000 m) approximately fill an HLLV payload bay, > 30 m long $\times$ 8.41 m diameter, allowed mass = 135,000 kg. All allowed mass is used while efficiently filling the available volume.

The free beams oscillate with frequency near 100 Hz and amplitude under $2y_L = 3.6 \times 10^{-3}$ cm, so the associated transverse velocity is 3.6×10^{-1} cm/s. But figure 5-28 shows that this input is attenuated by an order of magnitude in the bucket so that it is well within allowed limits, 0.1 cm/s at the bucket.

Mass Driver Throughput

Maximum throughput for a mass driver track, given a payload mass, appears to be constrained by payload spacing and by energy dissipation. Neither of these constraints appears to prevent throughputs greatly in excess of those in the baseline system.

As a linear synchronous motor, the mass driver permits discrete, accurate control of bucket locations. Separation of buckets should be maintainable so long as each is handled by a separate driven section. At two driven sections per bucket, 2 m per driven section, 1 km/s velocity, and 10 kg per bucket, maximum throughput would be 2500 kg/s. Since over 80 percent of the track operates at more than 1 km/s, special construction of the remaining 20 percent should add little cost. Possibilities include shorter driven segments to permit closer payload spacing or parallel feeder tracks interleaving payloads onto the main section.

An acceleration of 300 m/s^2 adds 300 J/kg for each meter of track. At 70 percent conversion efficiency, this deposits almost 130 J/(kg m); at the limit of 2500 kg/s this represents a heat load of 3.2×10^5 W for each meter of track. This in turn would require a radiator along the track some 300 m wide, if at the boiling point of water. Because much of this energy is lost to resistance in the bus and feeder conductors, these could be made of aluminum, thickened to reduce resistance, and made broad to serve as structural elements as well as self-cooling radiators. Such a system would reduce the need for active cooling.

APPENDIX G

THE MASS CATCHER

The catcher is equipped with radar capable of detecting payloads 10 s before arrival, that is, 2000 m away. A signal from the radar is processed to locate the spot at which the payload will cross the catch area, and the net is manipulated into that position for interception. Having captured the payload, the net and reel assemblies (rigs) act to decelerate it from its incoming velocity of 200 m/s to 20 m/s. The payload is then released into a storage depot and the rigs return to their original position by means of the closed loop tracks. The estimated cycle time is 60 s.

With 60 such rigs on a single catcher, it can catch 0.32×10^6 t/yr on a 100 percent duty cycle. In order to catch 11×10^6 t in 10 yr, 3.5 catchers on the average, have to be operational at all times, each catching from a separate stream of payloads shot from the same mass driver. The installation of 5 catchers at L_2 provides adequate margin for downtime for maintenance.

The time history of a payload and the rigs is shown in a two-dimensional representation in figure 5-29 and is detailed as follows:

The payload enters the catcher area with a velocity v = 200 m/s where it is decelerated constantly by 30 m/s^2. When its velocity reaches 20 m/s it is released to a storage depot attached to the rear end of the catcher frame. The reel assemblies and net motions are divided into three stages:

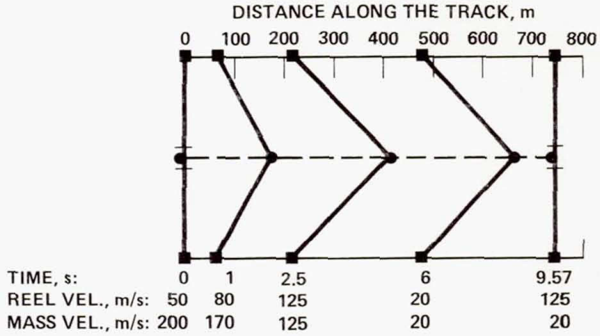


Figure 5-29.– *Two-dimensional representation of the sequence of events in the mass catcher.*

1. From zero to 2.5 s, reels are accelerated by pull from the payload while cords are being released until the velocity of the rig matches that of the payload.
2. From 2.5 to 6 s, both rig and payload are decelerated by a constant value of 30 m/s^2 until their velocity reaches 20 m/s. Energy is stored in spinning a flywheel in the reel assembly.
3. From 6 to 9.57 s, the cables are reeled in and the reel assemblies accelerated until the net clears the payload. The net is then pulled toward the inside track. The payload then proceeds on its own with constant velocity to the storage depot, while the rig circles around to the return track.

The above analysis is made for payloads arriving at the center of the circle enclosed by the triangular frame. If a Gaussian distribution is assumed most of the payloads arrive in this neighborhood. For payloads arriving away from the center a more detailed analysis is needed. It is expected that for such payloads, centering takes place initially and that by the end of the deceleration period the payload has been brought very close to the center. It is possible that some parameters may have to be adjusted to avoid any possibility of snarling.

APPENDIX H

TRAJECTORIES FROM THE MOON TO L_2

D'Amario and Edelbaum (ref. 27) have studied trajectories to L_2, originating tangentially to the lunar surface in low lunar orbit. Such trajectories are those of concern for transport of lunar material. Their work was performed in the circular restricted three-body problem. The results are shown in figure 5-30.

The trajectories fall into two classes: "fast" transfers and "slow" transfers. The latter involve looped trajectories and transfer times over 200 hr. While they lead to

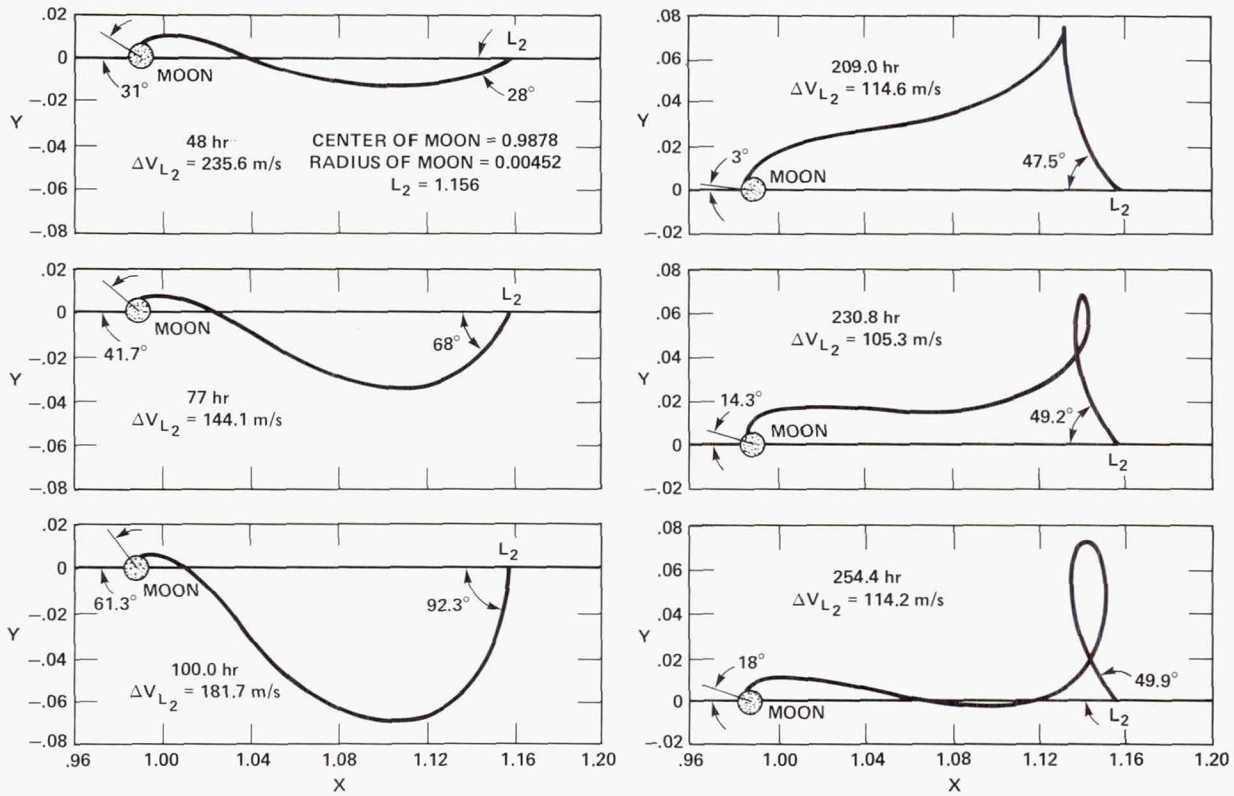


Figure 5-30.– *Integrated trajectories between the Moon and L_2 (after Edelbaum and D'Amario, AIAA Journal, April 1974).*

arrival at L_2 with velocities of only 100 m/s, approximately, they appear quite sensitive to small errors at launch and so are not of interest. The "fast" transfers involve transfer times under 100 hr and arrival velocities of approximately 200 m/s. Sensitivities of such orbits may be studied, at least when orders of magnitude only are of concern, by considering the transfer trajectories as conic sections in the two-body problem. A dynamic equilibrium may be sought between acceleration due to gravity and acceleration due to momentum flux. The equilibrium is unstable; nevertheless, the stationkeeping requirements associated with stabilizing the equilibrium may be much less than those associated with nulling out a momentum flux by continuous thrusting.

APPENDIX I

ROTARY PELLET LAUNCHER

The rotary pellet launcher (RPL) is a heavy tube rapidly rotating so as to accelerate small pellets of rock. The tube consists of a straight, nontapered section near the end and an exponentially-tapering section inward toward the hub from the nontapered section (see fig. 5-31). The notation is:

σ = allowable stress

ρ = material density

A_o = tube cross-section area at end

r_o = radial distance to end of tapered section

r_c = length of nontapered section

ω = rotation rate, rad/s

V_o = tip velocity = $(r_o + r_c)\omega$

The following equations define a design: For given V_o and ω,

$$r_o = \frac{1}{\omega}\sqrt{V_o^2 - \frac{2\sigma}{\rho}}\text{ , determination of } r_o$$

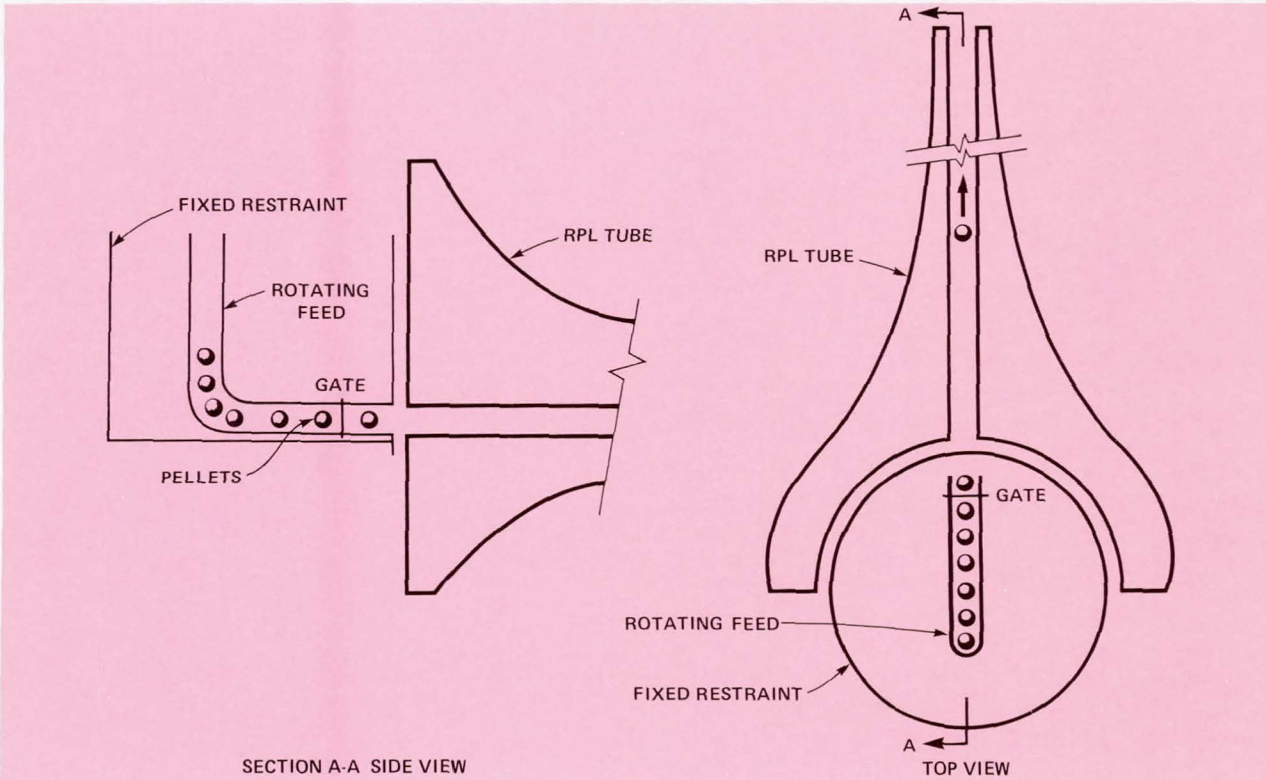


Figure 5-31.– *RPL injector schematic.*

$$A = A_o \exp\left[\frac{\rho\omega^2}{2\sigma}(r_o{}^2 - r^2)\right], \text{ taper of area for } r = r_o$$

$$m = A_o\rho\left[r_o\left(\frac{e^a \operatorname{erf}(\sqrt{a})}{\sqrt{a}} - 1\right) + \frac{V_o}{\omega}\right], \text{ mass of tube}$$

where $a = V_o{}^2/2\sigma - 1$ and erf is error function. Now let $L = r_o + r_c$. There exist the following ratios, given as functions of the dimensionless parameter a:

Length ratio: $r_o/L = \sqrt{a/(a + 1)}$

Area ratio: $A_{max}/A_o = e^a$

Mass ratio: $\dfrac{m}{\rho A_o L} = 1 + \sqrt{\dfrac{a}{a+1}}\left(1 + \dfrac{e^a \operatorname{erf}(\sqrt{a})}{\sqrt{a}}\right)$

The mass ratio is the ratio of RPL tube mass to the mass of a tube of the same density and equal length, with constant cross-sectional area A_o. Curves of the three ratios are plotted in figure 5-32.

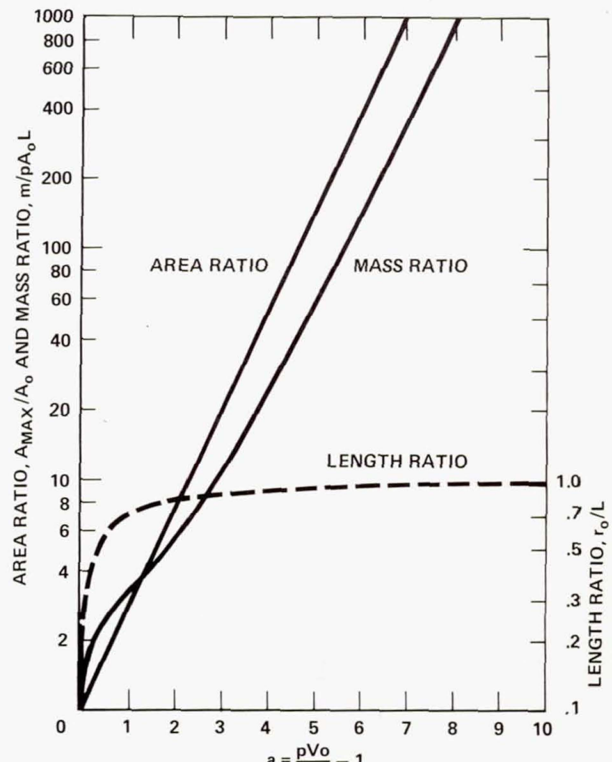


Figure 5-32.– *Estimating factors for RPL design.*

Typical materials of interest for use in an RPL are given in table 5-23. Here Sy is the yield strength in MPa; V_c is the critical velocity, $V_c^2 = 2Sy/\rho$. To build an RPL to eject pellets with velocity less than V_c, the launcher can be a straight tube of uniform cross section. But above V_c, the RPL must be tapered for part of its length, increasing in thickness toward the axis.

Note that $a = (V_o/V_c)^2 - 1$. Now consider a reference design. Let $V_o = 3965$ m/s. The material is Kevlar, at 60 percent of yield strength, or $\sigma = 2.2$ GPa (315,000 lb/in.^{2}). Take the density at 1.55 g/cm^3, or 7 percent higher than the tabulated value. Also let $A_o = 83.6$ cm^2, or a diameter of approximately 10.3 cm at the tip; L = 15.2 m. Then:

$$r_o = 13.8 \text{ m}$$

$$A_{max}/A_o = 97.8 \text{ (1.02 m diam at axis)}$$

$$a = 4.59$$

$$m = 8669 \text{ kg}$$

Now consider the bending stresses due to acceleration of the pellets. Suppose pellets of 10 g mass are accelerated. Near the tip the imposed acceleration is some 100,000 g. The pellet presses on the side of the tube with a force of approximately 8.9 kN, which is denoted F. The associated stress at any distance r from the tip has maximum value at the outside of the tube. Let the tube diameter there be d; the stress σ then is

$$\sigma \approx 32Fr/\pi d^3$$

and d^2 is proportional to A. A plot of σ as a function of radial distance from the axis is given in figure 5-33. Note that for the reference design, the stress is maximum some 2.44 m inward from the point where the tube ceases to taper. But even at that maximum, the stress is only some 7 percent of the yield stress for Kevlar. Stress relief may be provided by making the tube ellipsoidal in cross section.

The reference design is a rotating tube without counterweight. The lightest counterweight is not a solid block but is an exponentially tapering shape, like the tube. A double turret has a mass 17,340 kg. Two such turrets are needed, counterrotating, for the mass-catcher to maintain zero net angular momentum.

The catchers receive 40 kg/s at, say, 200 m/s for a force of some 8 kN. To null out, some 2 kg/s are ejected at 4000 m/s. For the dual turrets described approximately 200 pellets are ejected per second; each pellet is 10 g. The theoretical power required is $(1/2\dot{m}V_o^2 = 16$ MW. If provided by a space nuclear power system at 45 kg/kW this requires 7200 t.

To achieve thrust, the RPL must be made to release its pellets with approximate uniformity in direction. This may be accomplished with the pellet injector of figure 5-31. The feed tube rotates at the same rate as the RPL tube, pressing a pellet against the restraint. There is a hole in the restraint which lets a pellet through when the tubes are pointing in the right direction. A gate in the feed tube, controlled by a cam, ensures that only one pellet goes through at a time. Use of the gate means that the hole need not be small.

The RPL is subject to considerable wear due to friction and abrasion from the pellets, and must be designed for easy maintenance. This is accomplished by providing the tube with a removable liner, and by designing other high-wear parts for easy removal and replacement.

TABLE 5-23.– MATERIALS OF INTEREST FOR A ROTARY PELLET LAUNCHER

Material	e, g/cm^3	Sy, 10^3 MPa	V_c, m/s
Maraging steel	8.0	2.76	831
E glass	2.5	3.45	1663
Carbon fiber	1.4	2.76	1987
S glass	2.5	5.17	2036
Kevlar-49	1.45	3.62	2237
Fused silica	2.2	13.8	3545

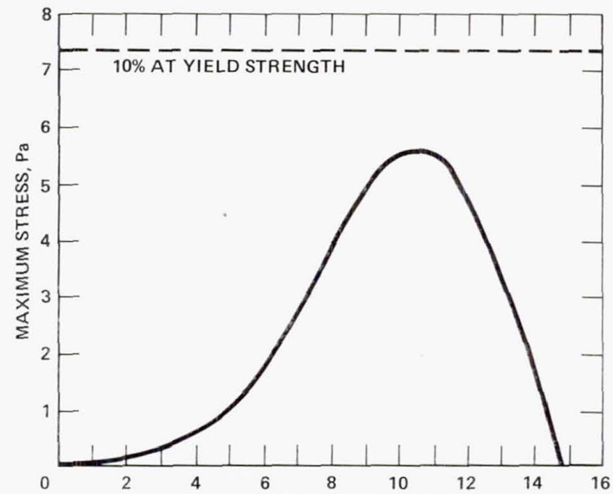


Figure 5-33.– *Bending stresses in reference RPL design.*

IMPACT UPON LUNAR ATMOSPHERE

The present lunar atmosphere, arising from natural sources with a total rate less than 0.010 kg/s, has a mass of less than 10^4 kg and surface number densities less than $10^7/\text{cm}^3$. The primary mass loss mechanism is due to the interplanetary electric field resulting from the motion of the solar wind. This causes rapid loss of gases to the lunar exosphere within 10^6 to 10^7 s. This loss has been confirmed by observations of lunar module exhaust gases (refs. 28, 29). If the atmosphere is dense, however, the cleansing effect of the solar wind decreases and thermal escape becomes the dominant loss mechanism due to the relatively higher collision rate among particles. The comparative effectiveness of these two loss mechanisms is illustrated in figure 5-34 for an oxygen atmosphere.

The use of the present lunar "vacuum" for industrial purposes as well as for scientific purposes (e.g., astronomical observations) will most likely necessitate the maintenance of a sufficiently "lunar-like" exosphere rather than allowing a substantial atmospheric mass to build up. Figure 5-35 presents growth curves of the lunar atmosphere for various constant gas addition rates. A release rate of about 10–100 kg/s would cause a transition to a long-lived atmosphere which occurs at a total mass of 10^8 kg (ref. 30). Release rates at about 1000 kg/s will produce an atmosphere which will exert aerodynamic drag on orbiting or departing vehicles (ref. 31). At gas release levels at or below 0.1 kg/s the lunar atmosphere would increase at most to a mass of 10^6 kg. Furthermore, if the artificial source of gas is shut off, the time scale for the Moon's atmosphere to return to its natural state is on the order of weeks (10^6 to 10^7 s). Due to the modeling techniques in determining these effects, order-of-magnitude accuracy should be attributed to these estimates.

Three sources can be identified within the framework of large-scale lunar operations as potentially releasing substantial quantities of gases into the lunar exosphere: mining and processing of lunar materials, leakages from the Moon base environment, and fuel expenditures during transportation of personnel and materials to and from the lunar surface. To build the Stanford Torus, raw material is propelled from the lunar surface by a mass launcher and not by the use of chemical rockets. Without materials processing on the lunar surface a potential source of gases is eliminated, and by using nonchemical

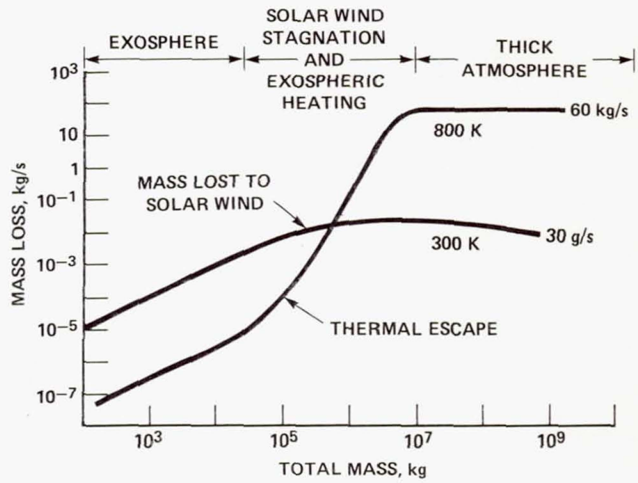


Figure 5-34.– *Loss rates for an oxygen atmosphere (mass = 16 amu). At a total mass of 10^8 kg, the lunar atmosphere approaches a constant rate of mass loss (after Vondrak, 1974).*

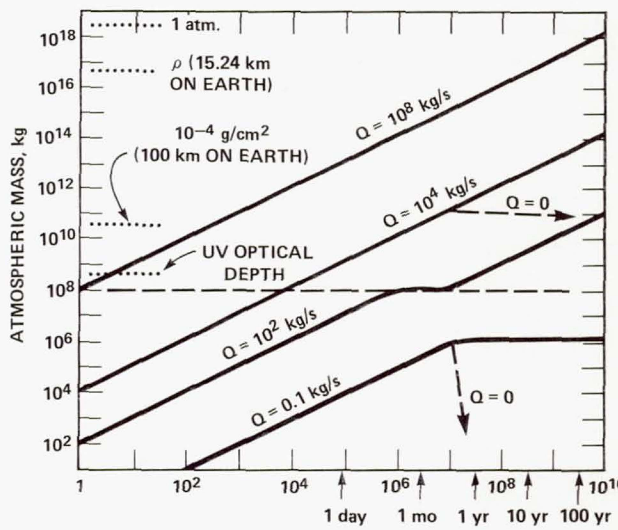


Figure 5-35.– *Growth of the lunar atmosphere for various constant gas addition rates. Comparable densities in the terrestrial atmosphere are indicated. Dashed lines indicate decay in the total mass if the gas source is shut off (after Vondrak, 1974).*

methods to lift the required lunar materials off the lunar surface, the mass released during transport through the Moon's atmosphere is minimized.

It is believed that mining operations will not release a significant amount of gases into the atmosphere. If it is assumed that 10^{10} kg of lunar materials are mined during a 10 yr period and that 10 percent of the trapped gases in the lunar soil (10^{-4} to 10^{-5} of its mass) are released during normal mining operations, the average release rate is 3×10^{-4} kg/s, which is substantially less than the natural source rate (personal communication from Richard R. Vondrak, Stanford Research Institute, July/August 1975).

Losses due to leakage from a Moon base have been estimated by NASA experts (ref. 18) based upon a projected loss rate per unit surface area. The yearly leakage loss is approximated to be 18,000 kg which would result in a release rate of 6×10^{-4} kg/s. Again this is insignificant in comparison to the natural source rate. It should also be noted that the Moon base considered by Nishioka et al. (ref. 18) includes a processing plant and would most likely be larger than the lunar facility considered here. The actual release rate would then be even smaller than that given above.

By far the most significant source for release of gases into the lunar environment is the exhaust products released by chemical rockets in the initial establishment of the lunar base and its continual resupply. It has been estimated that 1 kg of propellant will be expended by the lunar landing vehicle for each kilogram of payload landed (ref. 18). The mass of lunar base, estimated at 17×10^{6} kg, is assumed to be delivered to the lunar surface over a 2.5 yr construction phase. An annual resupply rate of $0.4–0.5\times10^{6}$ kg has been calculated. These figures give release rates of 0.2 kg/s during the establishment of the base and 0.02 kg/s thereafter by averaging the expenditures of propellant over an entire year. This is believed to be valid due to the rapid diffusion of gases released on the lunar surface (Vondrak, personal communication).

Although establishing a lunar base as required for the construction of the Stanford Torus will most likely result in gas release rates at times greater than that occurring naturally, a sparse lunar exosphere will still be preserved given the magnitudes of the calculated release rates. Furthermore, a long-lived atmosphere will not result and if the critical sources of gas are halted, the lunar atmosphere will return to its natural state within weeks.

APPENDIX K

CHEVRON SHIELDS

A particle radiation shield to transmit electromagnetic radiation in the visible region can be constructed out of right angle first surface mirrors made of aluminum. Figure 5-36 shows a cross section of such a shield.

If L is the separation between chevron mirror sections and d is the thickness of the mirrors, then the total cross sectional area of a chevron mirror is 2dL/cos 45°. If the mirrors were to be reformed as a uniform skin to cover the same area with the same mass of aluminum, the skin would have a thickness of 2d/cos 45° which is the path length traversed by a penetrating particle incident on the chevron shield at normal incidence.

Thus the average effective thickness of the chevron shield is the same as it would be if the mass were distributed uniformly to cover the same area.

When a chevron shield is used to admit light into a shielded region that contains a gas the individual angle mirrors must be connected by glass strips as shown in figure 5-36.

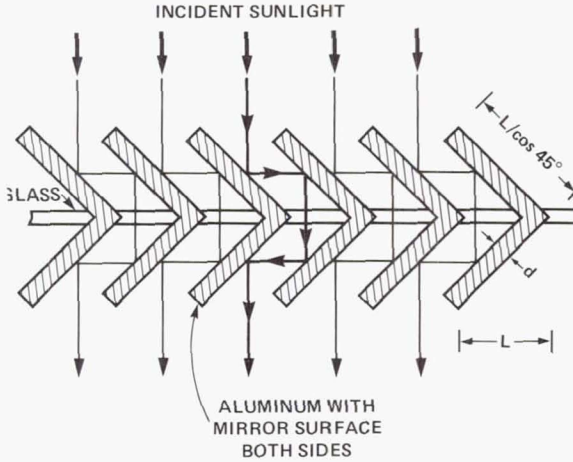


Figure 5-36.– *Cross section of the radiation chevron shield configuration.*

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6. Building the Colony and Making It Prosper

For the functioning system described in the previous chapter to become a reality much preparatory work must take place to fill in the gaps in current knowledge. Initial efforts toward space colonization begin on Earth, move into low Earth orbit (LEO) and continue later to the lunar surface, the site of the mass catcher (L_2), and finally to the site of the colony (L_5).

Critical gaps in present knowledge and experience, such as physiological limitations of a general population and dynamics of closed ecological systems, require extensive basic research before space colonies can be established. Parallel engineering efforts are also needed to develop suitable techniques, processes, and materials for colonization of space. Pilot plants for extraction of materials, for fabrication in space, and for power production are necessary to provide design and operations experience. Finally, transportation systems, in particular the mass launcher and catcher, and the rotary pellet launcher which are necessary for transporting lunar ore to L_5, must be developed early in the space colonization effort.

This chapter describes the projected preparations, operations, schedules, and costs to establish a permanent colony in space. While not optimized with respect to any criterion, they have been conservatively developed to demonstrate feasibility. The sequential activities needed for space colonization and the costs for such a program are summarized in figures 6-1 and 6-2.

Also included in this chapter is a discussion of the satellite solar power stations (SSPS's) as a potential economic justification for space colonization. If production of SSPS's were to become the central activity of space colonists, several modifications of the system logistics would be likely.

PREPARATORY WORK

There are three sites for research, development, demonstration, testing and evaluation (RDDT&E): Earth, LEO, and the lunar surface. There is no activity at L_5 during these activities because LEO provides a similar environment to L_5 but at one quarter the cost. This is because materials must come from the Earth during this preparatory work and it would cost more to transport them to L_5 than it does to LEO.

Activities on Earth

Systems not requiring zero-g can be developed in pilot plants on Earth. These include systems for materials extraction and fabrication, power generation, transportation, and habitation. Techniques for processing lunar soil into structural materials are especially critical for the colonization program since they differ significantly from those currently used on Earth (see chapter 4, appendices I and J). Those processes which require vacuum can be tested on a small scale on Earth. In addition, many of the large subsystems, while ultimately dependent upon the features of the locale in space, may be studied or partially developed on Earth. For example, a large facility or manufacturing plant may use lighter structures and different heat radiators in space; nevertheless, its internal processes can be studied in detail on Earth. These preliminary RDDT&E efforts are critical milestones for most major elements of space colonization.

Both nuclear and solar power sources of large scale must be developed, even though solar electric power is generally preferred since a specific plant mass of 14 t/MW is estimated for solar plants as compared to 45 t/MW for unshielded nuclear generators. Nuclear power is planned for the station in LEO and for the lunar base so that continuous power can be supplied during frequent or prolonged periods of being in shadow.

Two basic transportation systems must be developed; one to lift large and massive payloads, the other to transport lunar ore to L_5. The first system includes a heavy lift launch vehicle (HLLV) capable of lifting 150 t to LEO; an interorbital transfer vehicle (IOTV) with a 300 t payload for missions from LEO to high orbits; e.g., to L_2, L_5, or to lunar parking orbit; and a lunar landing vehicle (LLV) with a 150 t payload capacity. These vehicles can be developed using the technology developed for the space shuttle. Development of the lunar mass accelerator, the mass catcher at L_2, and the interlibration transfer vehicle (ILTV) is less certain but is still expected to use current technology.

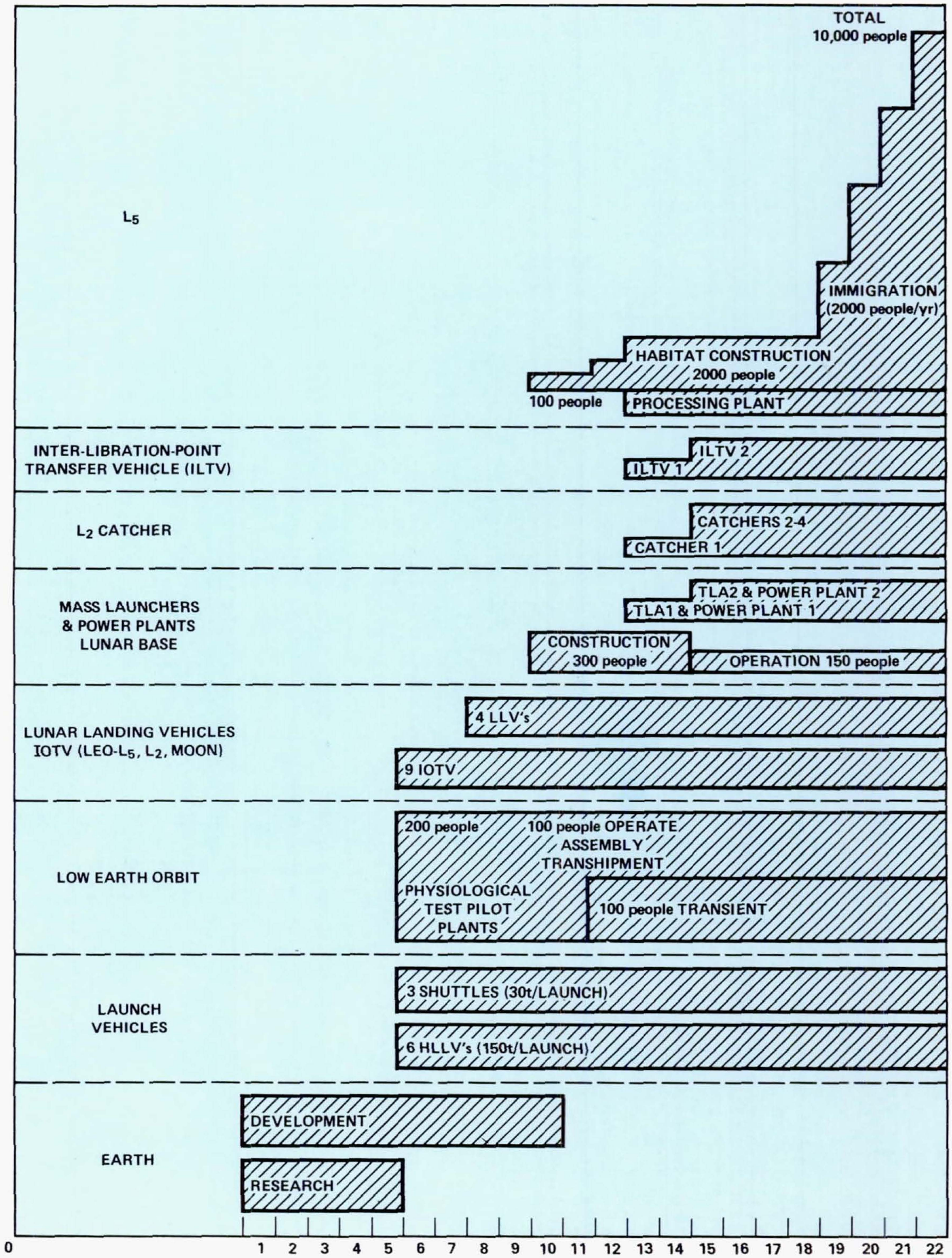

Figure 6-1.– *Mission profile. Blocks indicate activities or operational systems. Complete details are given in tables 5-5, 5-6, and 5-7.*

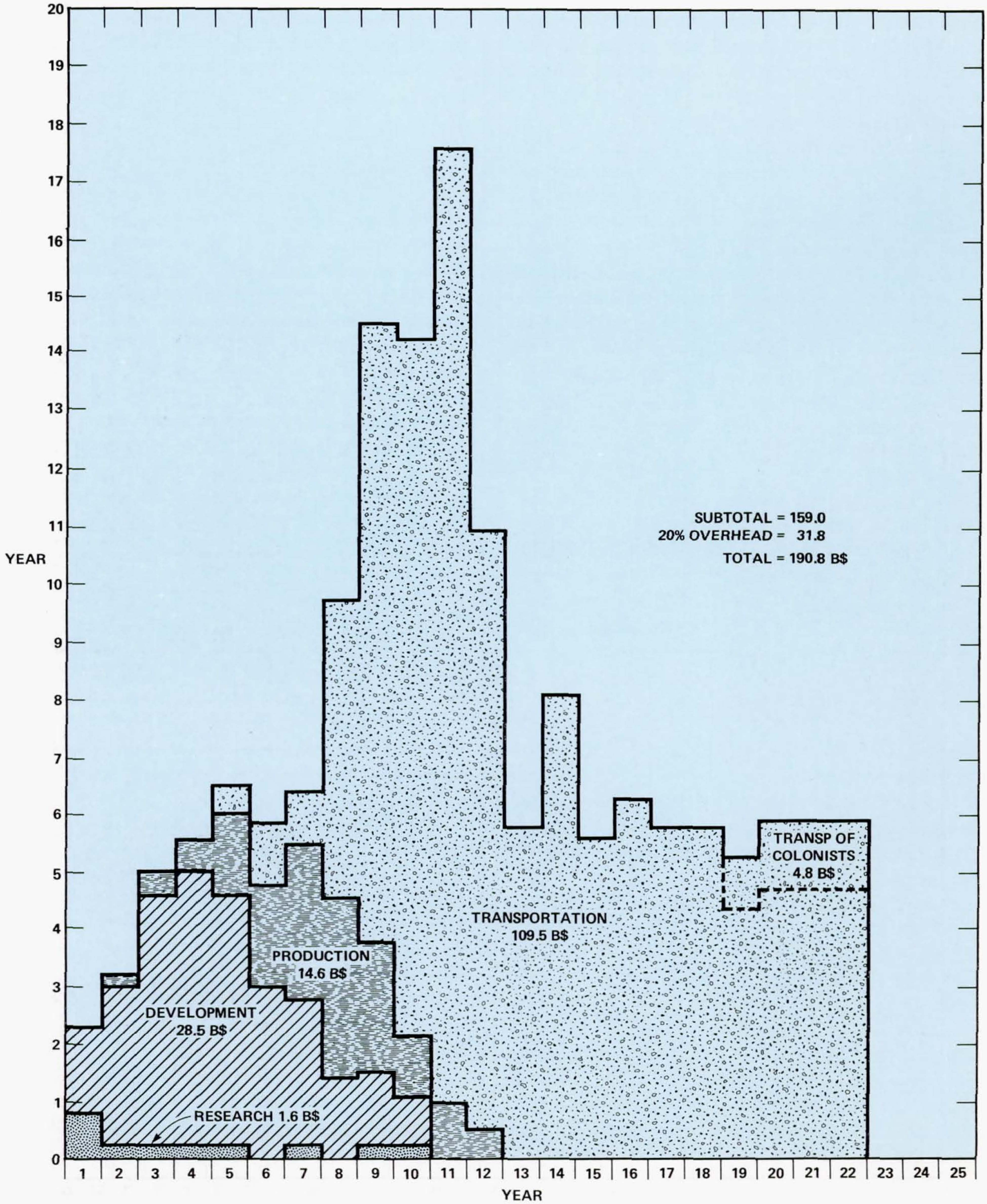

Figure 6-2.– *Cost summary. Transportation costs are reduced at year 12 due to oxygen available in space. Total costs are in 1975 dollars.*

Major research, as opposed to the above technological development, is required on physiological effects and ecological closure. The physiological effects that are amenable to research on Earth include long-term exposure to reduced total atmospheric pressure, to reduced pressures of certain gases, and effects of rotation on vestibular function. Research into questions of ecological closure is vital to the long-range colonization of space. The mix and quantity of flora and fauna needed to maintain closure or partial closure together with humans must be quantified. Moreover, research into intensive agricultural techniques is important in the colony's efforts to provide its own food. Particular attention must be directed to microbial ecology; the varieties, amounts, and interactions of bacteria and other microbes needed for healthy agriculture, animals, and people, are today imperfectly understood.

Activities at LEO

Pilot plants for materials extraction and fabrication, techniques for materials assembly, solar and nuclear power generation systems, the mass catcher, the ILTV and IOTV, and the habitats are all tested in LEO which provides vacuum and zero-g with relatively rapid access from Earth. Research on physiological effects of rotation and reduced gravity is conducted there also.

Activities on the Moon

Preliminary efforts on the surface of the Moon are minimal because the lunar systems can be evaluated and tested near Earth. Moreover, only limited lunar exploration is required (though more may be desirable) since undifferentiated lunar soil supplies the colony with sufficient minerals.

MATERIALS AND SUPPLIES

Materials for the total colony could come from the Earth. However, by using lunar raw materials as soon as possible, the costs to Earth of constructing the colony are greatly reduced, though the time required for completion of the colony is increased. Such a strategy is implemented by constructing only the essential components of the colony system from Earth materials. These subsystems – the lunar mining facility, the ore mass transport system, the L_5 materials extraction and fabrication facility, and the construction shack – are then taken to their respective positions in the system. Here they are made operational to process lunar raw materials for the major construction of the habitat. During this construction phase minor construction materials and supplies, as well as crew resupply, must come from Earth.

Fabrication on Earth

Low Earth orbit (LEO) serves as a vital point in the construction and supply of the first space colony. There, a space station consisting of a crew quarters, a construction shack, and a supply depot is assembled from materials made on Earth. Additional materials are then launched from Earth to LEO for assembly of the lunar base. They include a nuclear power station, a mass launcher and auxiliary equipment, mining equipment, crew quarters, and maintenance equipment. Also launched is equipment for L_2, the mass catchers and the interlibration transfer vehicle (ILTV). The construction shack, the solar power station and the supplies and facilities used in materials extraction and fabrication are launched to LEO for transfer to L_5.

Raw Materials from the Moon

Lunar mining operations proceed as described in chapter 5. Oxygen is an important by-product of the refining of lunar materials at L_5. It can be used there as rocket propellant immediately (resulting in a significant reduction in costs of transportation) or can be stored for later use in the atmosphere of the space colony and in its water.

Full use of all of the mass obtained from the Moon is assured by the manufacture of metals, glass, and soil, and by the use of ore and the slag in the cosmic ray shield.

Raw Materials from the Earth

The completed habitat must be outfitted with supplies and raw materials which are available only from the Earth, including highly specialized equipment and personal belongings of the immigrants to the colony. The atmosphere, water, and chemical systems also require raw materials from Earth; mostly hydrogen, carbon, and nitrogen which are not present in lunar ore. The initial agricultural biomass must be transported from the Earth to complete the outfitting of the habitat. From the time when immigration of colonists begins, only the resupply and new materials not available from the Moon are required from the Earth.

TRANSPORTATION AND CONSTRUCTION

Initially all of the supplied materials must be sent from Earth to LEO for transshipment to the point of activity. As operations begin at L_5 raw materials must be sent there from the surface of the Moon so that metals can be extracted and the construction of the colony can start.

Transshipment and Assembly in LEO

After the effort of research, development, demonstration, testing and evaluation there is a LEO station with pilot plants for processing materials and for producing nuclear and solar power. Because of the volume and weight limitations of HLLV payload capacity, large items are launched in subunits to be assembled in space. The payload capacity of the IOTV nominally equals that of two HLLV's, but in space neither volumes nor acceleration forces limit the configuration. Assembly tasks at LEO range from repackaging the mass launcher to setting up the complete solar power stations.

A propellant depot must also be established at LEO for use by the IOTV. When this additional propellant is taken into consideration, the mass which must be brought from Earth to LEO is roughly 4 times the payload delivered to L_5, and 8 times the payload delivered to L_2 or to the lunar surface. However, with the eventual availability of oxygen for rocket propellant as a by-product of refining at L_5, the mass which must be brought to LEO becomes approximately twice the payload to L_5 and 3.3 times the payload to L_2 or to the lunar surface (Austin, G., Marshall Space Flight Center, Alabama, personal communication, Aug. 15, 1975). These factors include return of transportation hardware to its point of origin following each mission.

Lunar Operations

Portions of the lunar base and the propellants for the lunar landing vehicle (LLV) are carried by the IOTV to a lunar parking orbit from which the LLV's ferry material to the lunar surface. As shipments arrive there, an assembly crew successively assembles the power plant, an underground habitat, the lunar soil scoop, and the mass launcher. Two separate nuclear power systems and 2 mass launchers are used to achieve the reliability needed. Their construction is timed to provide substantial operational experience with the first system before a second system is completed. The lunar base also includes a repair shop and a supply of spare parts for timely preventive maintenance and repairs.

Build-up at L_5

The construction shack and the first power plant are delivered to L_5 by the IOTV and are assembled by the construction crew. Thereafter, the materials extraction system and the fabrication system are constructed and made operational. Any lunar material received before the processing facility is completed is simply stockpiled.

ESTIMATING COSTS AND TIME

The subsystems, materials, supplies, and operations required for the build-up of the colony system have been outlined in the previous sections. It now remains to schedule the sequencing and timing of the events, and to determine the costs involved with this build-up. The scheduling and costing activities are interdependent.

System Considerations and Constraints

The scheduling and costing presented here are for the establishment of the baseline colony system described in chapter 5 through the completion and population of one habitat.

To allow ample lead time consistent with other large scale projects, the colony's development is scheduled with a gradual build-up of effort and with minimal fluctuations from year to year. Alternative strategies by which costs or project duration may be minimized are outlined briefly in appendix A. In general these results indicate that short durations are accompanied by large system costs. If interest costs are included, there is some minimum cost strategy. However, no optimization is attempted on the schedule presented here.

Automation is included only to the extent that it is now practiced in the industries involved. Bootstrapping (the use of small systems to build larger systems which, in turn, are used to build still larger systems) is not used in the cost estimate for the colony development, with the exception that pilot plants serve mainly to gain design and operational experience. The factors of additional time and added complexity of increased construction in space both caused the rejection of extensive bootstrapping.

Methods Used for Estimation

The scheduling and costing of a space colony require estimation of labor, size, and cost. First, labor: the personnel required in space for each major step of colonization is estimated from a composite of similar elementary tasks performed on Earth but derated or increased by the effects of vacuum and weightlessness. The methodology for estimating labor requirements is described in appendix D of chapter 5; the major results are summarized in table 6-1.

Next, sizes: the main items to be sized include habitats, vehicle fleets, and resupply and mass flow rates. The L_5 construction station and the LEO station are nominally 5 t/person with 7 t/person for the more permanent Moon base. The number of vehicles is twice that required for minimum turnaround time. Annual supply rates during construction are set at 1.7 t/person, which includes food, water, gases, and expendables. After the colony is available for habitation, the annual supply rate is reduced over the 4-yr colony build-up to an estimated 0.1 t/person.

The mass flow rate from the Moon is sized to complete the shield in 10 yr (1.2×10^6 t/yr). The materials extraction and fabrication plants are sized by the completion of the colony's shell in 6 yr (9×10^4 t/yr). Plant output is assumed (on the basis of an average of terrestrial industries) to be approximately 8.3 plant masses per year. Each power source is sized proportional to its respective power user.

These estimates for the transportation system, the mass and energy systems, and for the habitats are shown in tables 6-2, 6-3, and 6-4, respectively.

Finally, cost estimates are required for three categories of expenses – research and development through the first unit, purchase price of additional units, and

TABLE 6-1.– PERSONNEL REQUIREMENTS

	Number of people	Resupply,* t/yr	Time period,** yr	Rotation, people/yr	Tasks
LEO station	200	330	5-14	400	Physiological testing – rotation, gravity; pilot plant operations and testing; assembly systems for L_5 and Moon depot fuel
	100 (+ 100 transient)	250	15-25	200	Way station Supply transshipment
Lunar base	300	500	10-14	300	Assemble lunar systems
	150	250	15-25	75	Operate lunar systems
L_5 construction station:	100	167	9-11	100	Set up L_5 site
	2270	3784	12-18	2270	Build shell and 60 percent shield
L_5 colony	10000	4200† 1000††	19-22 23-25	100	Complete interior and shield Live and work
Inter-librational transfer vehicle	10	---	11-25	---	Crew for transfer between L_2 and L_5

*Nominal resupply: 1.7 t/person-yr of normal Earth materials costing $5/kg.

**Times are years from start of the project; e.g., if the project began in 1990 the time period 5-14 means 1995 to 2004.

†Colony resupply: Linear decrease from nominal value during 4-yr period of colony immigration.

††Colony resupply: 100 kg/person/yr of imports.

transportation costs. A precise costing effort for the first two items is prohibitively complicated. However, previous space projects have shown that research and development costs vary from $1000 to $20,000 per kg; Apollo was $14,000/kg. In this study $5000/kg is used. Purchase prices are assumed to be $500/kg which is consistent with other large-scale systems. Transportation costs, primarily launch and propellant costs and exclusive of vehicle costs, are based upon a manned payload of 30 people in each shuttle and an unmanned payload of 150 t per HLLV leading to $\$4.4 \times 10^5$ per person and $\$2 \times 10^5$ per tonne delivered to LEO. Outward beyond LEO, costs depend upon destination. They decrease with increased availability of oxygen in space from processing of lunar material.

These data are summarized in tables 6-2, 6-3, and 6-4 along with the size data. All costs are expressed on 1975 dollars.

Schedule

Scheduling of the colony build-up requires special attention to several key elements of the system; these include the habitats, the lunar nuclear power station, the lunar ore transportation system, the L_5 materials processing plant, the transportation costs, and the productivity of the L_5 work force.

Very simply, these factors interact in the following manner. Physiologically adequate crew quarters must be developed before any extraterrestrial activities can take

TABLE 6-2.– TRANSPORTATION SYSTEM

Vehicles	Route	Payload, t	R&D TFU,* $\$10^9$	Number of units	Cost/unit, $\$10^9$	Period, yr	Payload cost, $/kg
Space shuttle	Earth-LEO**	30	---	3	0.03	5-25	440
Heavy lift launch vehicle (HLLV)	Earth-LEO**	150	0.3	6	.08	4-25	200
Interorbit transport vehicle (IOTV)	LEO-LPO**	300	.4	9	.03	5-25	See trip costs below
Lunar landing vehicle (LLV)	LPO-Lunar surface**	150	1.7	4	.03	9-25	

TRIP COSTS: (Launch and fuel)	Without O_2 at L_5		With O_2 at L_5 (after year 12)***	
	Materials, $\$10^3$/t	People, $\$10^3$/person	Materials, $\$10^3$/t	People, $\$10^3$/person
Earth to LEO	200	440†	200	440†
LEO to L_5	600	400††	200	140††
LEO to Lunar surface	1400	930††	460	310††

*Research and development through first unit at $5000/kg.

**LEO: Low Earth orbit; LPO: Lunar parking orbit.

***Austin, G., Marshall Spaceflight Center, Ala., personal communication, Aug. 15, 1975.

†Earth to LEO for people via space shuttle, 30 people/flight (Hamaker, J., Marshall Space Flight Center, Ala., personal communication, Aug. 8, 1975).

††Crew transport module + people ≅ 2/3 t/person (Hamaker, J., Marshall Spaceflight Center, Ala., personal communication, Aug. 8, 1975).

All costs expressed in 1975 dollars.

TABLE 6-3.– MASS AND ENERGY SYSTEMS – SIZE AND COST

	Output size	Specific mass	Total mass, t	Time period, yr	R&D TFU,* $\$10^9$	Number of units	Unit cost, $\$10^9$
LEO							
Nuclear power pilot plant	10 MW	45 t/MW**	450	6-25	2.3		
Solar power pilot plant	20 MW	14 t/MW**	280	6-25 (moved to L_5 in year 9)	1.4		
Pilot materials plant	2500 t/yr of Al	8.3 output mass/yr / plant mass	300	7-25	1.5		
L_5							
Solar power plant 1	20 MW	14 t/MW**	280	9-25 (from LEO)	---		
2	50 MW	14 t/MW**	700	9-25		4	0.4†
3	50 MW	14 t/MW**		10-25			
4	50 MW	14 t/MW**		11-25			
5	50 MW	14 t/MW**		12-25			
Materials plant	90,000 t/yr of Al	8.3 output mass/yr / plant mass	10800	12-25		1	5.4†
Mass Transport Lunar Surface to L_2 to L_5							
Nuclear power plant 1	120 MW	45 t/MW**	5400	10-25		2	2.7†
2	120 MW	45 t/MW**	5400	14-25			
Mass launcher 1	5×10^5 t/yr	Track 1000t, Electrical 1000t, Repair shop 750t	2750	12-25	5.0††		
2	5×10^5 t/yr		2750	14-25		1	1.4†
Mass catcher 1	2.5×10^5 t/yr		340	11-25	1.7		
2	2.5×10^5 t/yr	Incl. solar power 10 MW/catcher, @ 14 t/MW	340	13-25		3	0.2†
3	2.5×10^5 t/yr		340	13-25			
4	2.5×10^5 t/yr		340	13-25			
Interlibration transfer vehicle (ILTV) 1	5×10^5 t/yr	Includes solar power 20 MW/ILTV @ 14 t/MW; 4-crew modules for 10 men	400	11-25	2.0		
(and crew module) 2	5×10^5 t/yr		400	12-25		1	0.2†

*Research and development through first unit at $5000/kg.

**NASA estimates for near term technology (nuclear plants are unshielded).

†Purchase at $500/kg.

††Active portions costed at $5000/kg for R&D TFU.

All costs in 1975 dollars.

place. Thereafter, lunar construction and mining can proceed only with the availability of the lunar nuclear power station. The shipment of lunar ore to L_5 requires that the mass launcher/catcher system be operational. Construction activities which use materials obtained from lunar ore depend crucially upon the development of materials extraction and fabrication techniques and upon the completion of the L_5 processing facility. Reduced transportation costs are possible as soon as oxygen in space is available as a by-product of the materials processing facility at L_5. Finally, the necessary work force which best matches the processing plant output, the desired rate of construction, and the available crew quarters requires careful consideration of the productivity of space workers.

These factors lead to the mission timetable which is summarized in figure 6-1. In brief, the schedule provides for 5 yr research on Earth, 3 to 5 yr for development and testing in orbit near Earth, 5 yr to build up operations on the Moon and at L_5, 6 yr for habitat construction, and a final 4 yr for completion of the shield and the immigration of the colonists. The overall schedule projects a 22 yr completion of the colony from the start of the project.

Specific details of this schedule for the space colony are given in tables 6-5 through 6-7.

TABLE 6-4.– HABITATS

	Crew size	Mass/person, t/person	Mass, t	Time period, yr	R&D TFU,* $\$10^9$	Unit cost, $\$10^9$
LEO station:	200	5**	1,000	5-25	5.0	
Lunar base:	300***	7**	2,100	11-25	1.1†	
L_5 construction station:	2,270	5**	11,350	9-19	5.7†	
L_5 colony:	10,000	---		20-25		
Structures			500,000			
Shield			10,000,000			
Interior						
Gas and H_2 from Earth			21,100		<.1††	
Biomass			5,900		<.1††	
Furnishings from Earth			25,000		.1††	
Colonists			600		---	
Soil			220,000			
Personnel transport modules: Number of units						
A: 3	10	0.6(+3)	9		.3†††	0.3†††
B: 4	100	.6(+3)	63		.2†††	.08†††

*Research and development through first unit at $5000/kg.

**Mass per person used is between the 10 t/person of the NASA 100 person space base and the 3.5 t/person of G. W. Drigger's design (paper presented at Princeton Conference on Space Manufacturing Facilities, May, 1975). The lunar base is expected to withstand the weight of lunar soil covering for shielding and to be more permanent.

***Designed for construction crew of 300; permanently occupied by operational crew of 150.

†Cost for first unit makes use of R&D done for LEO station; $500/kg purchased on Earth.

††Normal Earth materials costed at $5/kg.

†††NASA estimates.

All costs expressed in 1975 dollars.

TABLE 6-5.– SCHEDULE OF TASKS

Task	Mass t	Manpower, persons	Cost, $\$10^6$	Years after Go Ahead (1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17)
RESEARCH				
Closed ecology	---	400	1000	E* →
Physiological effects	---	200	500	E → O* →
Materials science	---	100	150	E →
DEVELOPMENT THROUGH FIRST UNIT				
Pilot plants				
Solar power (20 MW @ 14 t/MW)	280		1400**	E → O → L*>>***
Nuclear power (10 MW @ 45 t/MW)	450		2250**	E → O >>
Materials processing (7.0 t/day)	300		1500**	E → O >>
Transportation systems				
Heavy lift launch vehicle	(150)†		300††	E →>>
Interorbit transfer vehicle	(300)		400††	E → O >>
Lunar lander	(150)		1700††	E → O → M*>>
Mass system				
Mass launcher	2750		5000**	E → O → M >>
Mass catcher	340		1700**	E → O → L_2 >>
Interlibrational transfer vehicle	400	10	2000**	E → O → L_2 >>
Habitats				
LEO station (5 t/person)	1000	200	5000**	E → O >>
Moon station (7 t/person)	2100	300	1100†††	E → O → M >>
L_5 station (5 t/person)	11350	2270	5700†††	E → O → L >>
Crew transport module A	9	10	300††	E → O >>
Crew transport module B	63	100	200††	E → O >>
PRODUCTION				
Solar power plant 1 (50 MW)	700	---	350	E → O → L >>
2 (50 MW)	700	---	350	E → O → L >>
3 (50 MW)	700	---	350	E → O → L >>
4 (50 MW)	700	---	350	E → O → M >>
Nuclear power plant 1 (120MW)	5400	---	2700	E → O → M>>
2 (120MW)	5400	---	2700	E → O → M >>
Materials plant (Fab. & Ext.)	10800	---	5400	E → O → L >>

TABLE 6-5.– Concluded.

Task	Mass t	Manpower, persons	Cost, $\$10^6$	Years after Go Ahead 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Heavy lift launch vehicle 1	(150)		80	E → >>
2	(150)		80	E → >>
3	(150)		80	E → >>
4	(150)		80	E → >>
5	(150)		80	E → >>
Space shuttle 1	(30)	(30)	30	E → >>
2	(30)	(30)	30	E → >>
3	(30)	(30)	30	E → >>
Interorbit transfer vehicle 2-4	(300)	(450)	30X3	E → O >>
5-9	(300)	(450)	30X5	E → O >>
Lunar lander 2-4	(150)	(220)	30X3	E → O → M >>
Mass launcher 2	2750		1400	E → O → M >>
Mass catcher 2-4	340		20X3	E → O → L_2 >>
Interlibration transfer vehicle 2	400	(10)	20	E → O → L_2 >>

*E indicates effort on Earth, O in Earth orbit, M on the Moon, L and L_5, L_2 at L_2.
**Research and development costs are $\$5 \times 10^6$/t.
***>> denotes the time at which the system becomes operational.
†( ) indicates masses which are payloads.
††NASA estimates.
†††Construction cost is $\$0.5 \times 10^6$/t after experience gained at LEO.

TABLE 6-6.– LABOR SCHEDULE

Task	Years after Go Ahead: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Manpower, persons	
LEO	200 → 100 →
Lunar	300 → 150 →
L_5	100 → 2270 → 4K* 6K 8K 10K
Resupply, t/yr	
LEO	330 → 250 →
Lunar	500 → 250 →
L_5	167 → 3784 → 4200 → 1000
Crew rotation, persons/yr	
LEO	400 → 200 →
Lunar	300 → 75 →
L_5	200 → 100 → 2270 → 100 →

*K denotes 1000.

TABLE 6-7.– SCHEDULE OF PAYLOAD MASS FROM EARTH (kt)*

Years from Go Ahead:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Totals (kt)
MASS TO LEO																							
Materials					1.0	3.6	3.1	7.4	7.6	9.7	5.1	2.8	2.7	2.7									46.3
Resupply					.3	.3	.3	.5	.5	1.0	4.6	4.6	4.6	4.6	4.4	4.4	4.4	4.4	4.8	4.8	4.8	4.8	58.1
Colony interior													.6	2.5	6.0	7.0	6.4	6.0	5.2	6.2	6.2	6.2	52.3
TOTAL					1.3	3.9	3.4	7.9	8.1	10.3	9.7	7.4	7.9	9.8	10.4	11.4	10.8	10.8	10.0	11.0	11.0	11.0	156.7
Crew rotation** (100's of people)					4	4	4	6	5	8	8	30	30	30	25	25	25	25	4	4	4	4	
Colonists (100's of people)																			20	20	20	20	
MASS TO LUNAR BASE																							
Materials									2.7	5.0	2.8	.3	2.8	5.4									19.0
Crew rotation†										.2	.2	.2	.2	.2	.1	.1	.1	.1	.1	.1	.1	.1	1.8
Resupply										.5	.5	.5	.5	.5	.3	.3	.3	.3	.3	.3	.3	.3	4.9
TOTAL									2.7	5.7	3.5	1.0	2.5	6.1	.4	.4	.4	.4	.4	.4	.4	.4	25.7
MASS TO L_5																							
Materials								5.6	6.7	1.0	6.5	6.1											25.9
Crew rotation†								.2	.1	.1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	.1	.1	.1	.1	12.8
Resupply								.2	.2	.2	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	4.2	4.2	4.2	4.2	47.8
Colony interior													.6	2.5	6.0	7.0	6.4	6.0	5.0	6.0	6.0	6.0	52.3
Colonists (100's of people)																			20	20	20	20	
TOTAL								6.0	6.9	1.3	11.8	11.4	5.9	7.8	11.3	12.3	11.7	11.3	9.3	10.3	10.3	10.3	138.8

*Excludes fuel needed for further transport, though it is included in costs.
**Crew @ 2.2 t/person effective transport cost.
†Crew @ 2/3 t/person includes crew module.

TABLE 6-8.– COST TOTALS (1975 $B)

Years from Go Ahead:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Totals
RESEARCH	0.9	0.1	0.1	0.1	0.1	0	0.1	0	0.1	0.1													1.6
DEVELOPMENT TO FIRST UNIT																							
Pilot plants	.6	1.0	1.0	1.1	1.1	.3																	5.1
Transport systems	.1	.1	.4	.4	.5	.4	.5																2.4
Mass system	.2	.3	.8	.9	1.0	1.1	1.2	1.1	1.1	1.0													8.7
Habitats	.5	1.6	2.5	2.6	2.1	1.2	1.2	.3	.3														12.3
Subtotal	1.4	3.0	4.7	5.0	4.7	3.0	2.9	1.4	1.4	1.0													28.5
PRODUCTION																							
Power & materials				.3	1.0	1.6	2.3	2.8	2.1	.8	0.8	0.5											12.2
Transport		.1	.3	.3	.1	.1																	.9
Mass					.2	.2	.2	.3	.2	.2	.2												1.5
Subtotal		.1	.3	.6	1.3	1.9	2.5	3.1	2.3	1.0	1.0	.5											14.6
TRANSPORTATION													O_2 Available										
Crew to LEO					.2	.2	.2	.3	.2	.4	.4	1.3	1.3	1.3	1.1	1.1	1.1	1.1	0.2	0.2	0.2	0.2	11.0
LEO					.3	.8	.7	1.6	1.6	2.1	1.9	1.5	1.6	2.0	2.1	2.3	2.2	2.2	2.0	2.2	2.2	2.2	31.5
Lunar base									3.8	8.0	4.9	1.4	1.7	2.9	.2	.2	.2	.2	.2	.2	.2	.2	24.3
L_5								3.4	4.2	.8	7.1	6.8	1.2	1.6	2.3	2.5	2.3	2.3	1.9	2.1	2.1	2.1	42.7
Subtotal					.5	1.0	.9	5.2	9.8	11.3	14.3	11.0	5.8	7.8	5.7	6.1	5.8	5.8	4.3	4.7	4.7	4.7	109.5
Colonists																			1.2	1.2	1.2	1.2	4.8
TOTALS	2.3	3.1	5.0	5.6	6.5	5.9	6.3	9.8	13.5	13.3	15.3	11.5	5.8	7.8	5.7	6.1	5.8	5.8	5.5	5.9	5.9	5.9	159.0
MISCELLANEOUS and ADMINISTRATIVE (20% overhead)																							31.8
																							$190.8B

Cost Totals

The task, labor, and payload schedules of these tables are combined with the cost data of tables 6-2 through 6-4 to provide a schedule of costs. These results are summarized in figure 6-2. In addition, the total costs are given as: research, \$1.6 billion; development, \$28.5 billion; production, \$14.6 billion; and transportation, \$114.3 billion. Including a 20 percent overhead charge of \$31.8 billion, the total cost of the system is thus \$190.8 billion, where all costs are expressed in 1975 dollars. Figure 6-2 also shows that the availability of oxygen in space dramatically reduces the transportation costs which are still over half of the total system costs. A detailed breakdown of these cost data is given in table 6-8.

PRODUCTION OF ENERGY IN SPACE AS A POTENTIAL ECONOMIC JUSTIFICATION FOR SPACE COLONIZATION

The study looked into ways in which a space colonization program might be economically justified. One way, and perhaps the most promising, is production of SSPS's to satisfy terrestrial demands for energy. In the following sections the cost effectiveness of this production is discussed and important factors affecting economic viability are identified.

Beyond the Initial Cost Estimate

Costs can be reduced in several ways. Second and later colonies affect total costs, and space colonies have the ability to repay Earth for their initial and operating costs by supplying energy from space. Most of the repayment takes place after the first colony is finished and operating; in fact, the time horizon of the program has to be extended to 70 years. However, such an extension introduces cost uncertainties and suggests changes in the system that would be likely to increase its economic productivity.

Potential for Optimization Based on SSPS Production

A modified sequence to establishing colonies in space is to build several construction shacks first, and then begin building SSPS's and colonies at the same time. Additional workers (above the 4400 housed in the colony) should be housed in construction shacks. Shacks are more quickly built and cost less than colonies but have higher recurring costs of wages, crew rotation from L_5 to Earth, and resupply. Colonies have less total cost; that is, initial and recurring costs taken together. As production activities expand, more lunar materials are needed until the capacity of the initial mass launching system is exceeded. To move more material from the Moon will require more power there. Rather than add another nuclear station, an SSPS in lunar synchronous orbit should be considered since nuclear stations are probably cost effective on the Moon only before SSPS's are built in space.

Incorporation of these changes modifies the baseline mission timetable of space colonization operations after year 12, by building additional construction shacks and a lunar SSPS at L_5. Although start of construction of the first colony is delayed 3 years (see table 6-5), the colony is still completed by year 22.

The labor force in space also changes from the baseline system; it is smaller through years 12 to 14 and larger afterwards than that given in table 6-1. The initial construction shack houses only 500 people until year 15 when capacity is increased to 2000. By year 14, 3200 workers are needed, by year 15, 5389. No more construction shacks are required after year 15. New cost estimates reflecting these changes are given in column 3 of table 6-9.

At year 11 a rectenna must be built on the Moon to be ready to receive power from the lunar SSPS in year 15. Its receiving capacity is increased as needed in subsequent years. Parts of the rectenna can be fabricated on the Moon from lunar materials, for which chemical processing and fabricating equipment would be placed on the Moon at year 10. This equipment would also be used to expand the lunar base and to produce additional mass drivers. Costs of these lunar expansion activities are given in column 4 of table 6-9, including the cost of producing the lunar SSPS at L_5. (See appendix B for technical details of the power system.)

Profitable commercial production of terrestrail SSPS's at L_5 would not begin until year 22, although 9 demonstration units, each full scale, would be completed to prove the system during the previous 6 years.

Simultaneously with the SSPS demonstration, a second-generation shuttle system needs to be developed with lower operating costs than the current shuttle. The second-generation system would be justified by the increased traffic into space needed in a space colonization program. As an added benefit, the new shuttle could use propellants that would not pollute the Earth's atmosphere. The effect on costs of one candidate for a second-generation shuttle is shown in column 5 of table 6-9. (See also appendix C.)

Schedule, Costs, and Benefits of SSPS and of Additional Colonies

The U.S. market for electrical energy from space is assumed to be equal to the need for new plants because of growth in consumption and obsolescence of existing plants. The foreign market is assumed to be half of the U.S. market; that is, the same proportionately as for nuclear plants (ref. 1). Uncertainties in new technology delay its acceptance so that markets have to be penetrated. Ten years are assumed for full penetration of the electricity market by SSPS, which may be optimistic based upon current experience with nuclear power.

The market size is assumed to increase 5 percent per year, consistent with the intensive electrification scenario of the Energy Research and Development

TABLE 6-9.– ADJUSTMENTS IN BILLIONS OF 1975 DOLLARS TO THE COSTS GIVEN IN FIGURE 6-2*

(1)** Year of program	(2) Figure 6-2 costs	(3) Construction shack adjustments	(4) Lunar expansion & lunar SSPS power costs	(5) Transportation adjustments
1	2.8	–0.9		
2	3.7	↓		
3	6.0	↓		
4	6.7	↓		
5	7.8	↓		
6	7.1	↓		
7	7.6	–2.2		
8	11.8	–3.3		
9	16.2	–3.3		
10	16.0		2.29	
11	18.4		1.47	
12	13.8	2.54	1.47	
13	9.0	1.14	8.96	
14	9.4	2.07	8.96	
15	6.8			1.3
16	7.3			↓
17	7.0			↓
18	7.0			↓
19	6.6			↓
20	7.1			↓
21	7.1			↓
22	7.1			–4.5

*Cost of SSPS's which are built after year 14 and costs of second and later colonies are not included in this table. All costs given in this chapter include a 20 percent surcharge in miscellaneous items and administration.

**Indicates columnar numbers referred to in text.

Administration (ref. 2). Figure 6-3 gives the number of 10-GW capacity SSPS's needed each year to meet the terrestrial demand and the number of them actually transmitting energy (based on the assumption that each has a lifetime of 30 yr and begins to deliver power as soon as it is built in space).

Figure 6-4 shows the growth of the number of people and colonies in space if the only aim is to produce electricity for Earth. Other additional scientific or industrial activities in space would require larger populations.

Figure 6-5 shows production costs for SSPS's and colonies, and the benefits from electricity generated to terrestrial-based Americans. The economic advantage of space operations would be improved if benefits to foreign nationals from lower electricity costs, and to colonists, are included in the analysis.

An international organization to fund the colonization program would bring even greater benefits to terrestrial Americans as discussed later. But even an American-funded program would produce sufficient benefits, based on revenue obtained from sale of electricity and

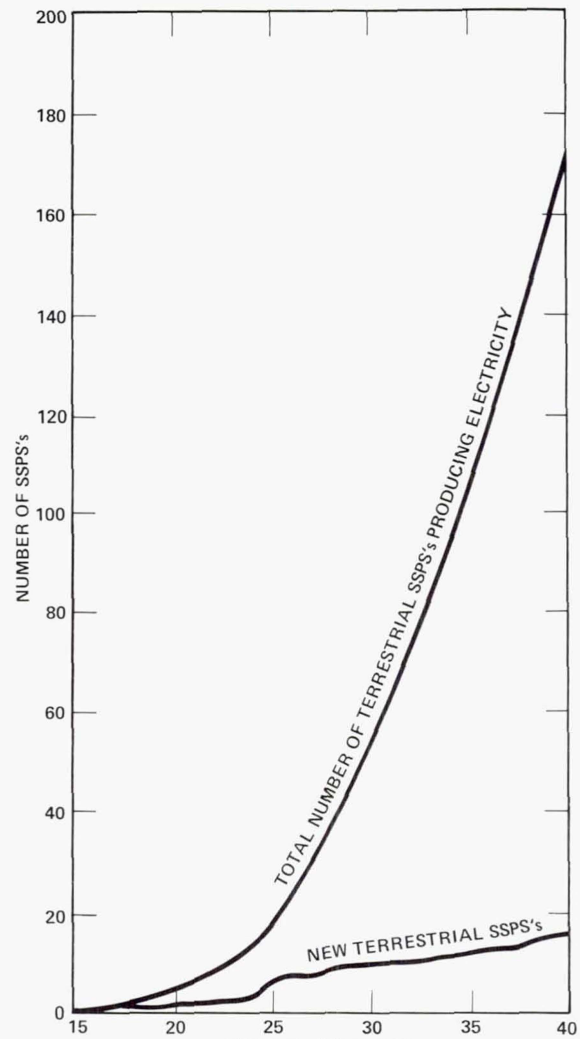

Figure 6-3. – *The production schedule for terrestrial satellite solar power stations.*

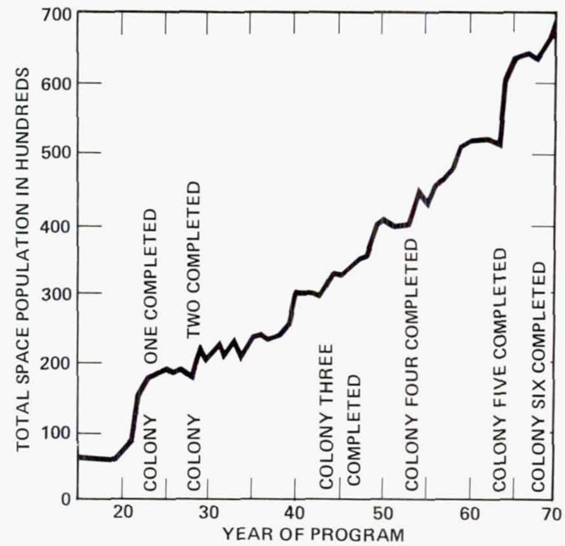

Figure 6-4. – *The production schedule for colonies.*

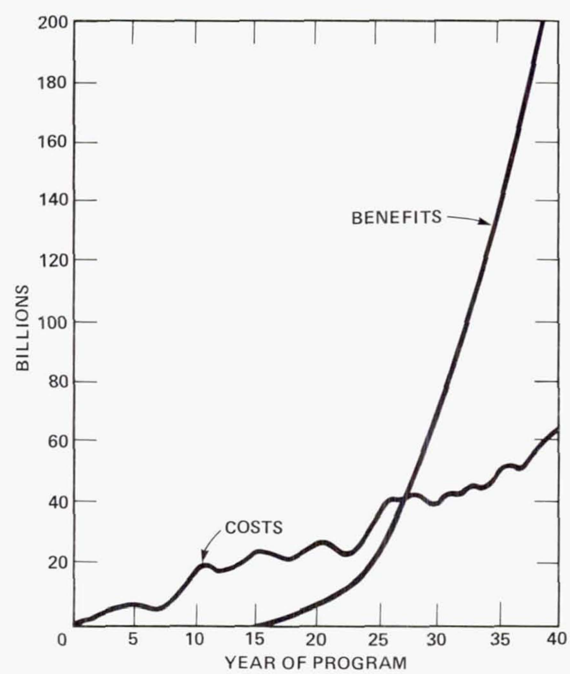

Figure 6-5. – *Total costs and electricity benefits.*

lower price of the electricity to the consumer. The costs for electricity (ref. 3) are discussed in appendix E. A competitive cost for space-derived electricity is 14.1 mils based on the assumption that the most economically-produced terrestrial electricity (from nuclear plants) will be 14.1 mils during the period under consideration. It is assumed that electric power consumption will not increase with price decreases and that all nations will be charged the same price.

Cash Flow and Other Results

A summary of cash flow – defined as the benefits less the costs for each year of operation in space – is given in figure 6-6. After year 12, costs are found to be dominated by building of SSPS's when mass starts to be transported from the Moon. The following 3 yr would be spent expanding the initial construction shack at L_5 and building an SSPS to be used to beam energy to the Moon.

By year 22 a new shuttle system is to be operating and commercial production of SSPS's begun. Colonists would start to arrive in year 20 and number 10,000, 3 years later. Costs then would be subsequently proportional to the number of SSPS's produced each year, and benefits proportional to the total number built, increasing more rapidly than costs.

Through completion of the first colony the program would cost \$196.9 billion, excluding costs directly related to SSPS's and more colonies (columns 1 and 5 of table 6-9). An additional \$14.7 billion would be needed to prepare for production of the demonstration SSPS's (columns 3 and 4 of table 6-9) which would cost \$21.7 billion more than the value of the electricity they produce.

By year 28 annual benefits would exceed costs. Payback in costs would be achieved.

Busbar cost of electricity produced from energy gathered from space is calculated to be 8.5 mils at year 22 falling to 4.8 mils by year 70 as shown in figure 6-6 (see also appendix D). The analysis is quite sensitive to the real discount rate (including inflation) which at 10 percent gives a benefit-to-cost ratio of 1.02. If the discount rate is lowered to 8 percent, the benefit-to-cost ratio is 1.5 (see appendix G).

Still Other Alternatives

The date at which a second-generation shuttle system becomes available is important. If development started at year 3 instead of year 15, the benefit-to-cost ratio could be increased to 1.3 and the cost of the program

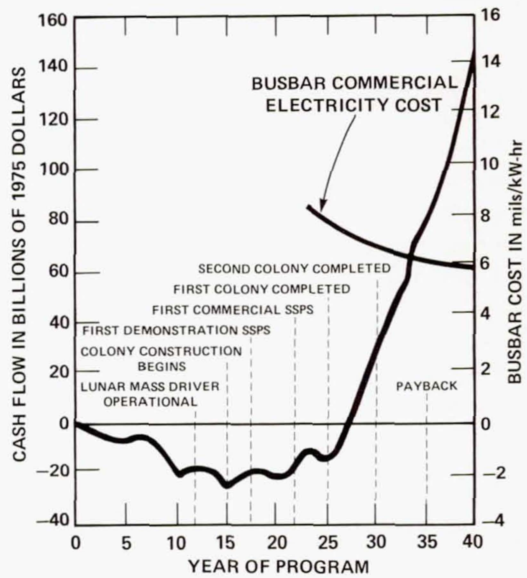

Figure 6-6.– *Cash flow (Benefits – Costs).*

for the initial colony would drop to \$112.7 billion, but with greater annual expenditures in the early years of the program.

There are alternatives to space colonization for generating electricity from space – building the SSPS's on Earth, and using construction shacks only without building any space colony. But space colonies win over terrestrial building because they use lunar materials which cost hundreds of times less at the use point in space than do terrestrial materials. While construction shacks cost less and can be built more quickly, in the long run they are more expensive because of their operating costs.

Some Other Energy-Related Benefits

While electricity from space and lower costs of electricity to U.S. consumers may be extremely desirable and sufficient to justify a space colonization program, there are other benefits that have not been fully evaluated in the study but may be significant. Environmentally, microwave transmission of power from space for conversion into electricity at Earth, is a very clean form of energy production (see appendix H). It avoids emission of pollutants into the Earth's atmosphere and minimizes the waste heat introduced into the terrestrial environment. The conversion of microwave energy to electricity is far more efficient than any thermodynamic process – 85 percent compared with a maximum of 50 percent.

Electrical energy from space may also be the only way in which the nation can become energy independent within the same time scale of 70 years, for not only can it supply the needed quantities of electrical energy but also inexpensive electrical energy that might be used for electrolysis of water to produce transportable fuels and thereby reduce dependence on petroleum products in transportation systems.

Another subtle energy-related benefit is the widespread nature of its application to mankind. Low-income people spend a comparatively greater percentage of their income on electricity than do affluent people. Thus lower priced electricity would benefit an enormous number of people and not just a few. This benefit from space colonization offers the potential of reaching vast numbers of people in the U.S. and providing relatively low-cost energy to many more in the developing nations of the world. It offers a real alternative to limited growth scenarios for underdeveloped peoples.

APPENDIX A

SPACE COLONIZATION COST PARAMETRICS

The simple, analytic expression used for estimating the costs of space colonization versus time is particularly useful as an aid in observing the effects upon costs due to variations in the system parameters. Moreover, it is formulated on a rate basis so that the results can be scaled as the technologies or strategies of colonization change. However, the equation cannot be used indiscriminately without regard to several precautions. The equation only models the system costs, giving approximate results. When the cost equation is placed on a rate basis it is assumed that the system costs scale linearly. To simplify the equation, a number of terms which were thought to be negligible or too difficult to formulate

TABLE 6-10.– PARAMETERS OF THE COST EQUATION

Symbol	Units	Definition	Baseline magnitude
M_5	kg	Mass of Al in L_5 habitat	5×10^8
O	kg/kg/yr	Ratio of L_5 plant output/yr to plant mass	8.3
E_5	kg/kW	Specific mass of L_5 power plant	14
K_5	kW/kg/yr	Power required per unit mass of Al produced at L_5	2.2×10^{-3}
W_5	kg/person-yr	Productivity of L_5 workers	46×10^3
F_5	yr^{-1}	Crew rotation rate for workers at L_5	1
H_5	kg/person	Mass of L_5 construction shack/person	5×10^3
D_5	$/kg	Launch costs to L_5	800
R	kg/person-yr	Re-supply rate for workers	1.7×10^3
M_m	kg	Mass to be launched from Moon	1.2×10^{10}
L_m	kg/kg/yr	Ratio of launcher mass to mass launch rate	4.6×10^{-3}
E_m	kg/kW	Specific mass of lunar power plant	45
K_m	kW/kg/yr	Power required per unit mass launched from Moon	2×10^{-4}
H_m	kg/person	Mass of lunar crew habitat/person	7×10^3
F_m	yr^{-1}	Crew rotation rate for workers at Moon	0.5
N_m	persons	Number of crew on Moon	150
D_m	$/kg	Launch costs to Moon	1600
Y	yr	Duration of the project – 8 yr	---

Note – Y is not the duration of the project, but 8 yr less.

were omitted, hence the results are too low. The 20 percent overhead charges were explicitly omitted. Finally, it is not easy to include parameters which change from year to year during the colony build up. In spite of these shortcomings, this equation is quite useful as a means of sensing cost trends which accompany changes in system parameters.

The major cost factors include research and development (R&D), production, transportation, and crew costs for the L_5 and lunar facilities. The other costs in the system have been neglected. An analysis of the R&D and production costs shows them to be relatively independent of modest variations in size. Data from table 6-9 show these costs to be 28.5×10^9 and 14.6×10^9, respectively, for a total of 43.1×10^9. Transportation costs to L_5 and the Moon are expressed as

$$T_5 = \left[\frac{M_5}{OY} + \frac{E_5K_5M_5}{Y} + \frac{H_5M_5}{W_5Y}\right]D_5 \tag{1}$$

and

$$T_m = \left[\frac{M_mL_m}{Y} + \frac{E_mK_mM_m}{Y} + H_mN_m\right]D_m \tag{2}$$

where all parameters of the system are defined and evaluated for the baseline system in table 6-10. Similarly, the crew costs are given as

$$C_5 = \left[\frac{M_5}{W_5Y}\right][RY + 600\ F_5Y]D_5 \tag{3}$$

and

$$C_m = N_m[RY + 600\ F_mY]D_m \tag{4}$$

When these results are added together, the total cost in 1975 dollars is obtained as

$$\begin{aligned}\$\ COST = {} & \frac{M_5}{Y}\left[\frac{1}{O} + E_5K_5 + \frac{H_5}{W_5} + \frac{RY}{W_5} + \frac{600\ F_5Y}{W_5}\right]D_5 \\ & + \left[\frac{M_m}{Y}(L_m + E_mK_m)\right. \\ & \left. + N_m(H_m + RY + 600F_mY)\right]D_m + 43.1\times10^9\end{aligned} \tag{5}$$

When the baseline values of the parameters from table 6-10 are substituted into eq. (5), the result is

$$\$\ COST\ (baseline) = \frac{3.7\times10^{11}}{Y} + 6.5\times10^{10} + 4.8\times10^8\ Y \tag{6}$$

These results are shown in figure 6-7. To demonstrate the use of the cost equation, two additional examples are also shown in the figure. In the first, a more advanced transportation system is considered which has $\$9\times10^9$ additional development costs, but which reduces the launch costs per kg to L_5 and the Moon to \$200 and \$400, respectively. The cost equation for this case is

$$\$\ COSTS = \frac{9.1\times10^{10}}{Y} + 5.8\times10^{10} + 1.2\times10^8\ Y \tag{7}$$

In the second, a solar power source, instead of the nuclear source, is used on the Moon with a resulting cost equation of

$$\$\ COSTS = \frac{2.5\times10^{11}}{Y} + 6.5\times10^{10} + 4.8\times10^8\ Y \tag{8}$$

Note that in the second case, this change is merely a convenient one for showing the use of eq. (5) and does not consider any of the related technical problems.

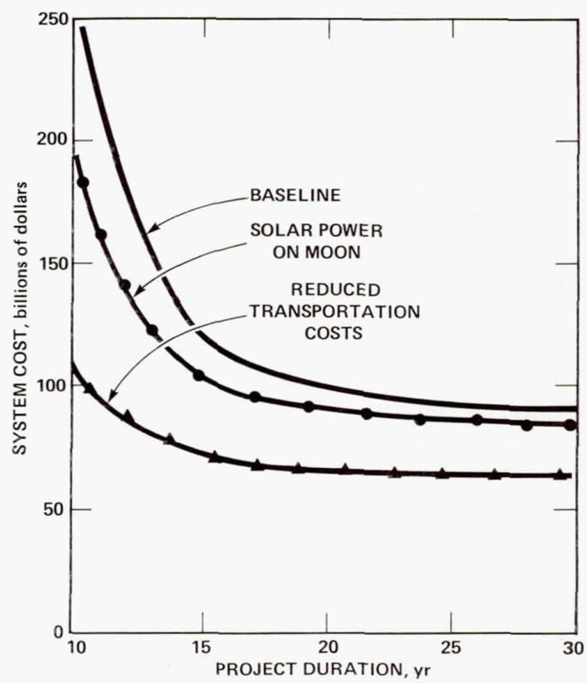

Figure 6-7.– *Parametric variations of system costs.*

Specific ideas to optimize the system include:

1. Major transportation vehicles to the Moon should not be returned until oxygen is available to reduce costs.

2. The interorbital transfer vehicle (IOTV) could be powered by a solar electric power source and ion or mass driver thrusters.

3. The lunar soil could be pre-processed on the Moon by magnetic separation.

4. Major structural elements and shell may be built by vapor deposition.

5. The colony site may be optimized by shortening either the lines of supply or the lines to ultimate usage site (geosynchronous orbit).

6. Better transportation vehicles to LEO would be very advantageous. A single stage to orbit, completely reusable, vehicle is desirable.

7. All wastes from the L_5 construction crews could be stored for recycling to offset losses of colony gases, carbon and water.

8. The torus can be shielded in stages by separate segments of complete thickness shielding for some groups of colonists to move in before the whole torus is shielded.

9. The throughput of the lunar mass drivers can be increased by providing additional power from a lunar satellite solar power station (probably at L_1, and using a shorter microwave wavelength from that used by the geosynchronous version).

10. The labor intensive industrial operations as presently employed on Earth can be more fully automated to reduce costs of the large labor force at L_5.

11. The usual administrative functions can be provided by people remaining on Earth.

12. Construction of agricultural facilities at LEO for providing food and for testing.

APPENDIX B

LUNAR SSPS POWER

Geosynchronous orbit is 35,400 km above the Earth, while L_1 (the location of SSPSs used for lunar power) is 64,400 km above the near side of the Moon. Thus, if lunar SSPSs are identical to terrestrial SSPSs, the microwave beam covers about twice as much area on the surface of the Moon as compared to Earth. Changing the wavelength can reduce beam spread but results in a loss in the (dc-to-dc) efficiency of the system. Terrestrial SSPSs are assumed to transmit at a 10 cm wavelength with 67 percent efficiency. Using information provided by Glaser et al. (ref. 4), the relationship between microwave efficiency and beamwidth leads to a lunar system with a wavelength of 3 cm, a 30 percent efficiency, and using a rectenna area of 27 km^2.

For the lunar system the rectenna is made up of 3,000 dipoles/m^2 and weighs 5 kg/m^2. All is produced on the Moon except gallium arsenide for the diodes and possibly some dielectric materials and glues which need to be brought up from Earth, amounting to about 0.6 kg/m^2.

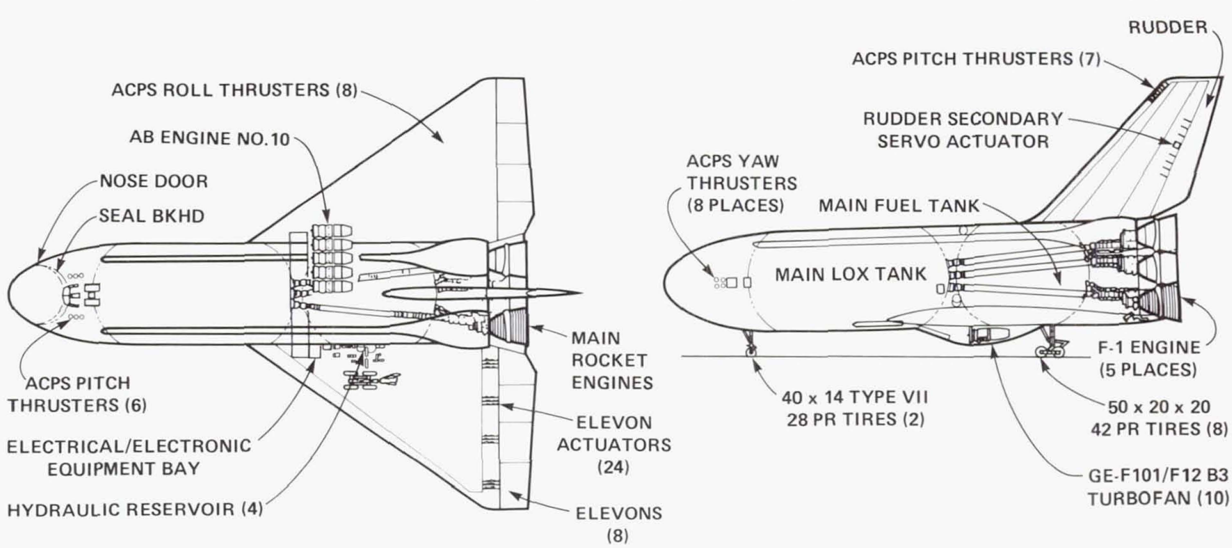

Figure 6-8.– *Flyback F-1 schematic views.*

APPENDIX C

THE FLYBACK F-1

The Flyback F-1 (fig. 6-8) is a winged, recoverable derivative of the Saturn V first stage. It was studied extensively in 1971 and Boeing proposed it for use as the first stage of the shuttle. Its development was estimated to cost $5 billion and to require a 7-yr lead time. It would replace the solid motors as the first stage of the HLLV. The propellants are mainly kerosene and oxygen. While the environmental consequences of kerosene are not as good as those of hydrogen, they are much better than those of solid propellant rocket motors. More research is needed to determine if this system could be made enviromentally sound for the 70-yr program of space colonization.

To guard against the possibility of cost underestimates in the earlier studies of the F-1 and to satisfy the need to develop a hydrogen-oxygen system for environmental reasons, this study assumes that the cost of the second generation system is $9 billion (rather than $5 billion) spread over a 7-yr period. Regardless of whether the F-1 or some other system is developed, performance characteristics are assumed to be a transportation cost to low Earth orbit of $55/kg of freight and $80,000 per person. Table 6-11 gives the transportation costs for people and freight to L_5 and the Moon over the whole program.

TABLE 6-11.– TRANSPORTATION COSTS

Year	Freight to L_5, $/kg	Freight to Moon, $/kg	People to L_5, $/person	People to Moon, $/person
1	---	---	---	---
2	---	---	---	---
3	---	---	---	---
4	---	---	---	---
5[1]	960	1920	1,008,000	1,644,000
6				
7				
8				
9				
10				
11				
12				
13[2]	480	792	696,000	900,000
14				
15				
16				
17				
18				
19				
20				
21				
22 & later[3]	110	182	160,000	206,000

[1] Before year 5 the program involves no transportation. The Space Shuttle and HLLV became available for use in year 5.

[2] O_2 becomes available in space for rocket propellant.

[3] The second-generation shuttle becomes available.

APPENDIX D

METHODS FOR ESTIMATING COST AND TIME FOR SSPS AND MORE COLONIES

Column 3 of Table 6-12 gives the number of new terrestrial SSPS's produced per year. The program is set up so that from the first year of production the level of output is always equal to the demand for terrestrial SSPSs, which is calculated in appendix E. That appendix shows that the level of demand depends in part on the year in which production begins. To determine demand, year 1 of the program is assumed as 1976.

To avoid undue complexity, composite variables are used in the analysis for two major variables – SSPS's and all colonies other than the first. Costs of a composite are obtained by aggregating costs of its components, including a charge for use of capital and an adjustment for the cost of maintenance. Methodology and costs of the major components are set forth in appendix F.

Costs for each of the composites are expressed by 5 variables whose initial values are: for an SSPS, \$9.73 billion plus the costs associated with obtaining 3,398 man-years of labor at L_5; 700 man-years of labor on the Moon; and 557 man-years of labor in other locations in space. In addition, the costs of 22.98 percent of a chemical processing and fabricating plant at L_5 is charged to the SSPS. These costs decrease over time due to learning curves and the introduction of the second-generation shuttle system. Second and later colonies are only produced after the second-generation shuttle system has been introduced. Their costs are also affected by learning curves. To begin with, colonies cost \$9.24 billion, 20,946 man-years at L_5, 1759 man-years on the Moon, 626 man-years elsewhere in space, and a chemical processing and fabricating charge of 0.5741 L_5 plants.

Man-year requirements for both SSPS's and colonies are assumed to decrease as additional units are produced with an 80 percent learning curve, found to be empirically valid in the aircraft industry (refs. 5,6). The level of output of new terrestrial SSPS's coupled with the labor costs of an SSPS and the assumption that an SSPS is produced within 1 yr, determine the number of workers needed at L_5 for SSPS construction, as given in column 4 of table 6-12. Column 5 of table 6-12 gives the number of new and old colonies. Columns 6 and 7 give the number of SSPS workers in colonies and construction shacks, respectively.

The timing of the nonlabor costs for building any particular colony other than the first is determined by assuming that expenditures are proportional to the labor input. Column 9 gives the number of new chemical processing and fabricating plants that are needed for a given year at L_5 to build the scheduled number of SSPS's and second and later colonies. The initial chemical processing and fabricating plant has a mass of 10,800 t. It all comes from Earth. The cost of material purchased on Earth for all plants is assumed to be \$600/kg. Taking into consideration the previously-mentioned learning curve and the cost of transportation for the year in question, the costs of all plants can be determined. Next, for each year, the average cost is computed of plants that have been placed at L_5 during that year or any preceding year for the purpose of building terrestrial SSPS's or second and later colonies. Similarly for colonies, the total nonlabor costs in dollars of terrestrial SSPS's and of second and later colonies are given in columns 10 and 11.

Column 13 gives the costs of labor. It is assumed that every colonist obtains 100 kg from the Earth annually and that the purchase price on Earth is \$5/kg. Luxury goods and various consumable goods produced within the colony make up the colonists' wages. The costs for a worker who is not a colonist consist of wages, crew rotation costs, and supplies from Earth. Wages cost \$120,000 per worker for each year spent in space. Each noncolonist also requires 1.67 t of supplies from Earth per year, costing \$5/kg purchase price on Earth plus transportation. Besides workers who live in construction shacks at L_5 all workers not at L_5 are assumed to be noncolonists. Column 14 gives the total costs.

The total of terrestrial SSPS's being used, column 15, is the sum of all terrestrial SSPS's built during the previous year or before, minus those worn out after an assumed lifetime of 30 yr. The derivation of the benefits listed in column 16 is discussed in appendix E.

The last column of table 6-12 gives the costs of the power produced after SSPS's come into commercial production. The cost of second and later colonies is thereby incorporated since they are needed to house the required labor. It is assumed that the resulting cost must be paid over the 30-year lifetime of the SSPS. A level charge for the 30-year period, which also covers interest at a real rate of 10 percent is then computed. The same procedure is followed so as to compute a level charge for all terrestrial SSPS's. To obtain the cost of electricity for a particular year, the level charges of all terrestrial SSPS's which produce electricity in that year are averaged.

APPENDIX E

ELECTRICITY BENEFITS

This analysis assumes that the funding organization is American as compared to international, and that the only benefits tallied are those which occur to Americans who remain on Earth.

Prices

The price of electricity is approximately equal to its cost plus a normal rate of profit. Busbar costs are the costs of power at the generation station; for SSPS's, the receiving antenna. They do not include the costs of distributing the power through the electrical grid to consumers. In 1974 the cost of electricity produced by nuclear (light water reactor) plants was 15 mils/kW-hr, by coal 17 mils, and by oil considerably more (refs. 3 and 7). The cost of electricity today is not as important as what it will be in the future. An optimistic projection is a constant price until 2045 of 14.1 mils (ref. 7).

There are several terrestrial-based technologies such as the fast breeder reactor, fusion, and central station solar which might be developed during the period under consideration. The least expensive of these will probably be able to produce electricity at 11.6 mils, not including a charge for development costs. When the latter cost is taken into consideration as well, it is reasonable to take 14.1 mils as the price which space colonization power must meet to be competitive (Manne, A., personal communication, June 24, 1975).

The market for electricity can be divided into two types, baseload and peakload. The baseload market is where the sources which generate electrical power are run until maintenance requires a shut-down. Peakload plants are run for much less time to satisfy fluctuating demands for electricity with the hour of the day and the time of year.

All of the costs given in appendix D assume that the electricity produced is used in the baseload market. Since space colony power is cheaper than its competitors, all new baseload plants are likely to be SSPS's.

Manne and Yu (ref. 7) project a fixed cost of a constant 7.2 mils for coal and 9.6 mils for nuclear, while the variable costs are 12.0 mils for coal and 4.5 mils for nuclear. The costs of peakload power are the fixed costs plus a fraction of the variable costs which depends on the amount of plant utilization. In the absence of space colonization, coal will dominate the peakload market, as well as be important in the baseload market. The fixed cost of 7.2 mils for coal suggests that space colonization power will not compete in much of the peakload market. When new plants are needed for the peakload market, rather than build new coal plants, it would be more economical to convert some of the coal plants from the baseload to the peakload market and replace the loss in the baseload market with SSPS's.

For the foreign market it was assumed that no power would be sold to other nations for the first 2 years after the introduction of the first power plant. Afterward, one-third of the power produced would be sold abroad. This level of exports is consistent with past experience of building and selling nuclear, central-station electric power reactors (ref. 1).

The growth rate of electricity demand is assumed to be 5 percent per year. The Energy Research and Development Administration's scenarios, for 1975–2000 (ref. 2), involve a growth rate of 5.7 percent for intensive electrification. Since space colonization could lead to a large supply of low-cost electricity, it would imply that a 5 percent growth rate appears reasonable. The 5 percent growth rate was chosen to be consistent with a price of 14.1 mils. The consistency of a 14.1 mil price and a 5 percent growth rate is supported by Manne and Yu (ref. 7) and Hudson and Jorgenson (ref. 8).

The fact that new technology offers more risks than established technology results in fewer sales than the market size indicates. This occurs, even though the new technology is cheaper, because some potential customers who would otherwise be buying hold back, waiting to see if the new technology actually works. The percentage of the U.S. market size assumed obtainable for each of the first 10 years after the initial terrestrial SSPS is operational is: 10, 12, 16, 20, 25, 32, 40, 45, 50, 60. From then on it is 100 percent.

A 30-year lifetime is assumed for an SSPS. This is the typical lifetime of Earth-based electric power plants. At a 5-percent growth rate for 30 years, the market grows by a factor of 4.3. Therefore, the market for new plants due to growth is taken as 4.3 times as large as the market for replacement.

The number of new terrestrial SSPS's that can be sold per year and the ways in which this changes over time is calculated and given in column 3 of table 6-12. An example is to calculate the number for year 20. In 1975 the U.S. consumed 224 GW of electricity. At a 5 percent growth rate this will be 594.34 GW by year 20. The additional power needed for growth in year 20 is 5 percent of this. In addition, there is the replacement market which is such that the growth market is 4.3219 times as large. To take into account the foreign market, multiply by 1.5. Finally, since this is only the sixth year in which terrestrial SSPS's have been produced, take 40 percent of the foregoing to correct for market penetration. This gives 21.96 GW. SSPS's are assumed to be utilized 95 percent of the time, with the remainder being required for maintenance. Thus, to provide this level of power, 2.31 power stations of 10 GW are needed.

TABLE 6-12.– COSTS AND BENEFITS OF A PROGRAM OF SPACE COLONIZATION IN 1975 DOLLARS [1]

(1)[2] Year of program	(2) Adjusted figure 6-2 costs[3]	(3) Number of new terrestrial SSPS's	(4) SSPS labor at L_5,[4] hundreds	(5) Number of colonies,[5] new, old	(6) SSPS workers in colonies,[5] hundreds	(7) SSPS workers in construction shacks at L_5, hundreds	(8) Labor at L_5 used to build second and later colonies,[4] hundreds	(9) Number of new chemical processing & fabricating plants being used at L_5 to build SSPS's & 2nd & later colonies[4]
1	1.9							
2	2.8							
3	5.1							
4	5.8							
5	6.9							
6	6.2							
7	5.4							
8	8.5							
9	12.9							
10	18.3							
11	19.9							
12	17.8							
13	19.1							
14	20.4							
15	8.1	1	27			27		3
16	8.6	1	24			24		0
17	8.3	1	22			22		0
18	8.3	1	21			21		0
19	7.9	1	19			19		0
20	8.4	2	35		7	28		2
21	8.4	2	33		22	11		0
22	2.6	3	46		37	9	31	3
23	0	3	43	(1,0)	43	0	55	1
24	0	4	53		44	9	45	2
25	0	7	86		44	42	12	6
26	0	8	90		44	44	8	2
27	0	8	84		44	40	14	0
28	0	9	89		44	45	3	2
29	0	9	83	(2,0)	83	0	0	0
30	0	9	80		80	0	0	0
31	0	10	85		85	0	0	2
32	0	10	82		82	0	0	0
33	0	11	86		86	0	0	3
34	0	11	82		82	0	0	0
35	0	12	90		88	0	0	2
36	0	13	93		88	5	0	2
37	0	13	88		88	0	0	2
38	0	14	95		88	7	0	3
39	0	15	97		88	9	12	2
40	0	15	97		88	9	41	2
41	0	16	98		88	10	40	2
42	0	17	104		88	16	34	2
43	0	18	104	(1,1)	74	30	20	2
44	0	19	110	(2,1)	110	0	0	1
45	0	20	109	(2,1)	109	0	0	2

TABLE 6-12.– Continued

(10) SSPS costs,[4,6] billion $	(11) Costs of second and later colonies, billions $	(12) Total space population,[7] hundreds	(13) Labor costs,[4] billions $	(14) Total costs,[8] billions $	(15) Total terrestrial SSPS's in use	(16) Benefits, billions $	(17) Cash flow (benefits-costs), billions $	(18) Costs of space colonization electricity once commercial SSPS's are being built
				1.9			−1.9	
				2.8			−2.8	
				5.1			−5.1	
				5.8			−5.8	
				6.9			−6.9	
				6.2			−6.2	
				5.4			−5.4	
				8.5			−8.5	
				12.9			−12.9	
				18.3			−18.3	
				19.9			−19.9	
				17.8			−17.8	
				19.1			−19.1	
				20.4			−20.4	
8.3		64	6.4	24.7			−24.7	
7.6		63	5.7	23.8	1	1.2	−22.6	
7.1		62	5.4	22.7	2	2.3	−20.4	
6.9		62	4.8	21.9	3	3.5	−18.4	
6.6		61	4.5	24.9	4	4.7	−20.2	
12.5		71	7.2	27.6	5	5.8	−21.8	
11.9		87	4.5	28.3	7	8.1	−20.2	
12.4	1.7	159	3.1	24.8	9	10.5	−14.3	
12.0	3.0	176	3.9	24.1	12	13.9	−10.2	8.5
15.4	2.5	179	4.1	30.0	15	17.4	−12.6	8.3
26.0	.7	187	4.5	36.9	19	22.0	−14.9	8.1
28.5	.4	186	4.5	41.8	26	30.2	−11.6	7.7
27.7	.8	187	4.5	41.5	34	39.4	−2.1	7.5
30.4	.2	181	4.3	43.9	42	48.7	4.8	7.3
29.5	0	220	2.0	40.5	51	59.1	18.6	7.1
29.1	0	212	1.8	39.9	60	69.6	29.7	7.0
31.8	0	224	2.0	43.5	69	80.0	36.5	6.9
31.3	0	216	1.9	42.9	79	91.6	48.7	6.7
34.0	0	227	2.0	46.2	89	103.2	57.0	6.6
33.4	0	216	1.9	45.5	100	115.9	70.4	6.5
36.5	0	233	2.2	49.5	111	128.7	79.2	6.5
38.9	0	239	2.4	52.8	123	142.6	89.8	6.4
38.3	0	233	2.0	51.5	136	157.7	106.2	6.3
41.2	0	242	2.6	55.5	149	172.7	117.2	6.2
43.4	.8	258	3.3	60.0	163	188.9	128.9	6.2
43.4	2.6	291	4.9	63.6	178	206.3	142.7	6.1
45.6	2.5	291	4.9	66.2	193	223.7	157.5	6.0
48.4	2.1	292	5.0	69.3	209	242.3	173.0	5.9
50.4	1.3	291	4.9	70.7	226	262.0	191.3	5.9
53.2	0	323	2.6	70.3	244	282.8	212.5	5.8
55.8	0	320	2.6	73.5	263	304.8	231.3	5.8

(See footnotes on next page.)

TABLE 6-12.– Concluded

[Footnotes]

[1]The analysis runs for 70 yr. The numbers for the last 25 yr corresponding to table 6-12 are not given. They may, however, be calculated by the reader if desired. All of the required data are given within this chapter.

[2]Indicates columnar numbers referred to in text.

[3]These costs are obtained by summing the costs in table 6-9.

[4]All learn curves with respect to SSPS's, colonies, and chemical processing and fabricating plants, have the first unit given in the table as the second unit in a learning curve since one colony, one SSPS, and one plant were produced previously and have their costs accounted for as part of the adjusted costs of figure 6-2.

[5]Second and later colonies which are finished in year X are assumed to provide their full complement of labor in year X-1. The first colony is assumed to be complete except for 37.5 percent of its radiation shield by the beginning of year 20. The colony is then slowly occupied. One-sixth of its full complement of export labor being available in year 20, one-half in year 21, five-sixths in year 22, and all of it thereafter. By the beginning of year 23 the colony has been completed.

[6]The initial SSPS dollar costs can be divided into a constant cost of $2.48 billion and a variable cost of $7.26 billion. The introduction of the second-generation shuttle system reduces these numbers to 1.99 and 4.77, respectively. The variable cost falls in accordance with an 80 percent learning curve until it has decreased by a factor of six. (See footnote 4.)

[7]All numbers in this column can be calculated from information given in table 6-12 except for the entries for years 15 through 22. These use as additional inputs the amount of labor related directly or indirectly to the first colony. In chronological order these inputs are 2671, 3010, 3214, 3316, 3486, 1375, 1375, and 1375 man-years.

[8]To help maintain a reasonably smooth pattern of expenditures, $4 billion which, according to the algorithm, should have been spent in year 20 is moved to year 19. For similar reasons $2 billion is moved from year 25 to year 24. In practice these changes could be accomplished by purchasing on Earth some of the components for SSPS's the year before they are actually needed.

APPENDIX F

COMPOSITE VARIABLES FOR SSPS AND ADDITIONAL COLONIES

Due to the nature of the calculations discussed in appendix D it was necessary to construct composites by making separate aggregates for each. One is for the nonlabor, nonchemical processing and fabricating plant costs, and is expressed in dollars (the dollar costs). Three of the aggregates are for the number of man-years of labor needed at L_5, on the Moon, and elsewhere in space. The final aggregate is a charge for the amount of chemical processing plants used at L_5.

The dollar cost aggregate is the sum of three parts. These are: the present value, with respect to the time at which the item was completed, of all future costs associated with maintenance and operation; a capital charge for the use of any capital other than chemical processing and fabricating plants at L_5; and the costs of the actual physical components. As a simplification, construction is assumed to take place within a year, thus allowing interest charges on components used in the early phases of construction to be ignored. The error introduced (because in actuality construction, especially in the case of colonies, takes longer than a year) is small.

A capital charge is defined as the constant amount that must be paid every year of the life of some capital good so that the present value of these payments is equal to the cost of the capital good. This definition assumes that the productivity of the capital good is the same for every year of its life. It follows that if the life of a capital good is infinite and the real discount rate is X percent, then the capital charge is X percent of the cost of the capital. The capital charge is higher when the lifetime is finite but not very much higher if the lifetime is long (30 years or more), as is the case in essentially all of the capital in this program. In particular, for a real discount rate of 10 percent and a lifetime of 30 years, the capital charge is 10.37 percent. As a simplification, all of the capital charges assume an infinite lifetime.

The three labor and the chemical processing and fabricating plant aggregates are calculated in precisely the same way as the dollar cost aggregate, except that instead of using dollars of cost, man-years of location-specific labor or plants are substituted.

The costs of the components along with other costs are given in table 6-13. It may be expected that costs will fall with time. To simplify, all of the component costs which enter the dollar aggregate are assumed constant, purposely chosen somewhat lower than costs would initially be and considerably higher than they would eventually be. Note also that all of the components in table 6-13 are produced at least partly in space. Besides component costs, the table also gives the direct costs for SSPS's and second and later colonies. It is the transformation of these direct costs into dollar costs, location-specific labor costs, and plant costs, which gives the composite variables.

There are two SSPS composite variables; one for when oxygen is available in space but the second-generation shuttle system is not; the other for when both are available and hence transportation costs are lower. To show in some detail how the composite variables are made, a rough derivation of the second of the two composite variables mentioned above is given here.

Essentially, all of the data needed are in table 6-13 and its footnotes. The cost of material bought on Earth is, from column 3, \$4.61 billion. This includes \$1.01 billion for the rectenna on Earth. The transportation cost of the material bought on Earth is, according to column 4, \$0.66 billion. The annual nonlabor costs for maintenance and operation are, as stated in column 7, equal to \$30 million. The present value at the time of construction of this, assuming as an approximation an infinite lifetime for the SSPS's, is \$0.3 billion. Total dollar costs thus far are \$5.57 billion.

Column 5 shows that the direct labor costs are 2950 man-years, all at L_5. Labor costs of maintenance and operation are obtained (as in the case of the nonlabor costs) from the present value by multiplying the annual figure by 10. This gives 300 workers at a location other than L_5 or the Moon. To be precise, the 300 are at geosynchronous orbit where the people attend to the SSPS once it is in operation. The cost of the housing accommodations for the workers at L_5 is not included in the composite variable. This is dealt with by the methodology described in appendix D. Workers not at L_5 have their housing costs counted into the variable. The 300 geosynchronous orbit workers are assumed to live in construction shacks. From the information provided in table 6-13, this costs \$0.09 billion for parts bought on Earth, \$0.0165 billion for transportation, 75 man-years at geosynchronous orbit, and 0.0135 of a chemical processing and fabricating plant.

Transportation costs from Earth to every place of relevance for these calculations are assumed to be the same as the costs from Earth to L_5. Taking 10 percent of all of the costs of construction shacks given above in order to obtain the appropriate capital charges gives \$0.0107 billion, 8 man-years, and 0.00135 plants. The 8 man-years require housing, and the 0.00135 plants require lunar rock as input. The costs of these are small enough to ignore. Everything is now included within the SSPS aggregate except for a direct chemical processing and fabricating plant capital charge of 0.199 plants and 11990 kt of lunar rock needed as input to these plants.

To get the lunar rock within a year requires 4.0 interlibrational transfer vehicles (ILTVs). From table 6-13, the capital charges for these are: \$0.0142 billion for parts bought on Earth and transportation, 40 man-years at L_5 for construction, 0.0014 plants, and a negligible amount of lunar rock. In addition, annual maintenance and operations costs are 44 man-years at L_5. The present value of this is 440 man-years, and the capital charge, which is the relevant number, is 44 man-years. Twenty percent of the mass coming off the Moon is used as fuel for the ILTVs. Thus, 2488 kt are needed from the Moon. To catch it, 8.0 mass catchers are needed. The resulting charges are \$0.0057 billion, 184 man-years not

TABLE 6-13.– COSTS OF VARIOUS ITEMS[1]

(1)[2] Item	(2) Capacity	(3) Costs at purchase of parts bought on Earth, $\$10^9$	(4) Transportation for parts bought on Earth when oxygen and the 2nd-generation shuttle system are available,[3] $\$10^9$	(5) Costs & location of labor for construction, man-years	(6) Number of chemical processing & fabricating plants needed[4]	(7) Annual maintenance & operation costs
SSPS[5]	10 GW at busbar on Earth	4.6100	0.6600	2950 at L_5	1.9900	\$30 million 30 man-yr not at L_5, not on Moon
2nd & later colonies	10,000 persons	.2595	7.3090	19,820 at L_5	5.0000	[6]
Interlibrational transfer vehicle	500 kt/yr delivered to L_5 [6]	.0300	.0055	100 at L_5	.0035	11 man-yr at L_5
Mass catcher	Catches 313 kt/yr	.0060	.0011	100 not at L_5, not on Moon	.0033	13 man-yr, not on L_5, not on Moon
Mass driver[7]	625 kt/yr	.4507	.1367	700 on Moon	0	75 man-yr on Moon
Moon base	100 persons	.0721	.0219	25 on Moon	0	[6]
Lunar rectenna	448 GW at busbar	17.4312	5.2875	2777 on Moon	0	[6]
Construction shacks	100 persons	.0300	.0055	25 at construction shack location	.0045 at L_5	[6]

[1] All costs are in 1975 dollars.

[2] Indicates columnar numbers referred to in text.

[3] Transportation costs from Earth to those places denoted as not at L_5 and not on the Moon are assumed to be the same as transportation costs from Earth to L_5.

[4] In order to work at full capacity, a chemical processing and fabricating plant requires an input of 1,000 kt of lunar rock annually.

[5] All costs for these items are before the effects of learning curves have been taken into account. These effects are discussed in appendix D. Do not overlook footnote 6 of table 6-12.

[6] An ILTV must start at the mass catchers with 625 kt of lunar rock in order to deliver 500 kt to L_5.

[7] A mass driver requires 0.12 GW to run at full capacity.

at L_5 or on the Moon, 0.00264 plants, and negligible lunar rock. The 184 man-years of labor are derived from workers housed in construction shacks for which is charged \$0.0065 billion, 5 man-years which are not at L_5 or on the Moon, and 0.00083 plants.

On the Moon 4.0 mass drivers are required. The charges for these are \$0.235 billion and 580 man-years on the Moon. All of the plants discussed thus far were at L_5. Their costs are converted to dollar costs by the algorithm given in appendix D. The costs of the plants on the Moon are measured in terms of dollars needed to purchase parts on Earth and the dollars needed to pay for the transportation of these parts to the Moon. These dollar costs are included in the amounts given in columns 3 and 4 of table 6-13.

The power used by 4.0 mass drivers is 0.48 GW. This is 0.1071 of the 4.48 GW that an SSPS with lunar rectenna can deliver. The capital charge for this fraction of a rectenna is \$0.2433 billion and 30 man-years on the Moon. Thus far, there is a total lunar labor charge of 610 man-years. The capital charge for the lunar base additions that these people require is \$0.0573 billion and 15 man-years of labor on the Moon.

One final item is needed: 0.1071 of an SSPS beaming power to the Moon. The costs of such an SSPS are the same as the costs of the SSPS being evaluated, except that the \$1.01 billion for a rectenna on Earth need not be paid. Thus, building one SSPS requires 0.1071 of a second SSPS plus $(0.1071)^2$ of a third SSPS plus $(0.1071)^3$ of a fourth, and so on. The sum of this series is 1.1199. Therefore multiplying all the previous costs by 1.1199 and subtracting \$0.1211 billion for the Earth-based rectenna correction gives the final result of a cost of \$6.76 billion, 3398 man-years at L_5, 700 on the Moon, 557 not at L_5 or the Moon, and 0.2298 chemical processing and fabricating plants.

These costs of the SSPS variable are for when both oxygen in space and the second-generation shuttle are available. To obtain the costs of the SSPS variable when only oxygen is available, the transportation costs given in column 4 of table 6-13 are adjusted in accordance with the information given in table 6-10. The result is a cost of \$9.73 billion with the nondollar costs remaining the same.

Colony composite variable costs are found by a similar method. A somewhat rougher calculation than that for the SSPS yields \$9.24 billion, 20,946 man-years at L_5, 1759 on the Moon, and 626 elsewhere. From table 6-13 it is seen that the direct dollar costs are \$7.57 billion. This direct cost may be broken down as follows: plants and animals cost, including transportation, \$0.68 billion; nitrogen in the atmosphere and H_2 for H_2O cost, including transportation, \$2.42 billion; high technology equipment from Earth and personal belongings cost, \$2.88 billion. Finally, \$1.6 billion is needed to pay for transportation for 10,000 colonists.

APPENDIX G

CONCEPTS FOR ESTIMATING PROFITS FOR THE COLONY

The total benefit (revenue plus consumer savings) is 14.1 mils per kW-hr for electricity which is sold to Americans. For an SSPS that has a capacity of 10 GW and an assumed utilization of 95 percent, this produces annual benefits of \$1.173 billion. Power sold to foreigners yields 13.6 mils of benefits per kW-hr which amounts to \$1.132 billion annually for each SSPS. All the power produced in the first 2 years after the initial terrestrial SSPS is built is sold to the U.S. Afterwards one-third of the power produced is sold abroad. An SSPS is assumed to begin to produce power the year after it is completed. As an example, table 6-12 shows that in year 20, 5 terrestrial SSPS's are producing power. The benefits obtained are therefore \$5.783 billion.

Subject to certain qualifications discussed below a project should be undertaken if and only if the value of its benefits exceeds the value of its costs (see ref. 9). It is important to include *all* benefits and *all* costs, even those which are not normally expressed in monetary terms, such as the value of any damage done to the environment. In our society there is usually a positive interest rate. This is a reflection of the fact that society values the consumption of a commodity today at a higher value than the consumption of the same commodity in the future. This fact must be taken into consideration when the value of benefits and amount of costs are determined. To do this the benefits and costs which occur in the future must be discounted. For example, if a project pays as benefits or has costs amounting to \$B in every one of n + 1 consecutive years, then the value of the benefits or what is technically called the present value of the benefits is equal to:

$$B + \frac{B}{1 + r} + \frac{B}{(1 + r)^2} + \ldots + \frac{B}{(1 + r)^n}$$

where the benefits and costs are measured in real dollars (that is, dollars of constant purchasing power) and where r is the real discount rate.

Under certain idealized conditions the real discount rate is the same as the real rate of interest. The latter is essentially the rate of interest observed in the marketplace less the rate of inflation. Empirically the idealized conditions needed to make r equivalent to the real rate interest do not hold, resulting in a considerable divergence between these two parameters. The size of this divergence and hence the appropriate value of r is the subject of an extensive, unresolved debate among economists. The value of r which is currently used by the Office of Management and Budget is 10 percent. This is considered by most economists to be reasonable if not conservative.

Having introduced several concepts, it is now possible to be precise about what is meant by the benefit-to-cost ratio. It is the present value of the stream of benefits divided by the present value of the stream of costs. When this ratio is greater than one, then the project, subject to certain qualifications, is worthwhile. It is worth noting that if a benefit-to-cost ratio is, for example, 1.2, then if the costs in every year of the program were increased by as much as a factor of 1.2, the project would break even in the sense that the benefits would equal the costs where the costs include a real rate of interest equal to the real discount rate.

There is no reason why a project cannot be of infinite length having an infinite stream of benefits and costs. Normally, the present value of these streams and hence the benefit-to-cost ratio is finite. In the space colonization program a 70-year period is selected, not because a finite period is needed but for other reasons. In particular, if one goes too far into the future, various assumptions begin to break down. For instance, a 5 percent growth rate in electrical power cannot continue forever, especially since much of this growth rate is due to a substitution of electricity for other forms of energy. An additional consideration is that when employing a real discount rate of 10 percent, whatever happens after 70 years has little impact on the benefit cost ratio.

The term payback has been applied to a number of differing concepts. The most common form of usage is adopted for this study; namely, that payback occurs when the principal of the original investment has been repaid.

APPENDIX H

ENVIRONMENTAL IMPACT OF MICROWAVE POWER TRANSMISSION

The proposed system to transmit solar power to the Earth's surface involves microwaves as the conduit of energy beamed from Earth-orbiting solar power stations through the atmosphere. Primary concerns about the impact upon the environment of such a system are:

1. Beam drift
2. Biological effects of radiation
3. Electromagnetic interference

The microwave beam from the satellite solar power station (SSPS) is triggered by a pilot signal beamed from the center of the receiving antenna to provide the necessary phase control to produce a coherent beam. Otherwise, if the beam were to drift, its coherence would be lost, the energy dissipated, and the resulting power density would approximate normal communication signal levels on Earth (ref. 10).

Radiation effects depend on the power density of the transmitted beam which in the present system is designed for a peak of 10–100 mW/cm^2. In the United States and other nations of the Western world, 10 mW/cm^2 is an accepted standard for radiation exposure, while the Eastern European nations have placed acceptable exposure limits as low as 10 μW/cm^2 (ref. 4). It is noted (ref. 11) that the U.S. Department of Health, Education and Welfare has set a limit for new microwave ovens of 1 mW/cm^2 at a distance of 5 cm. The major biological effect of continuous microwave irradiation at levels between 10 and 100 mW/cm^2 is believed to be heating. Human exposure can be minimized by providing shielding for the personnel stationed in the rectenna area and by limiting public access to regions in which the Gaussian power distribution is below acceptable radiation levels. The system could be designed so that the microwave power density at 10–15 km from the center of the beam would be at most 10 μW/cm^2, meeting the lowest international standards for continued exposure to microwaves. Passengers in aircraft flying through the beam should be more than adequately protected by the metallic skin as well as the short transit times involved. By fences and a metallic screen under the rectenna, plant and animal life can be protected. Birds flying through the beam would experience elevation of body temperature (ref. 4). Radiation effects do not appear to present substantial problems to transmission of power from space, but more research is required.

System efficiency and lack of atmospheric attenuation suggest 10 cm as the wavelength for transmission. The corresponding frequency, 3 GHz, can be controlled to within a few kHz (ref. 11). Due to the high power involved, electromagnetic noise could potentially interfere with radar, microwave and radio frequency communications, and possibly with radio astronomy. This will necessitate further restrictions near the rectenna.

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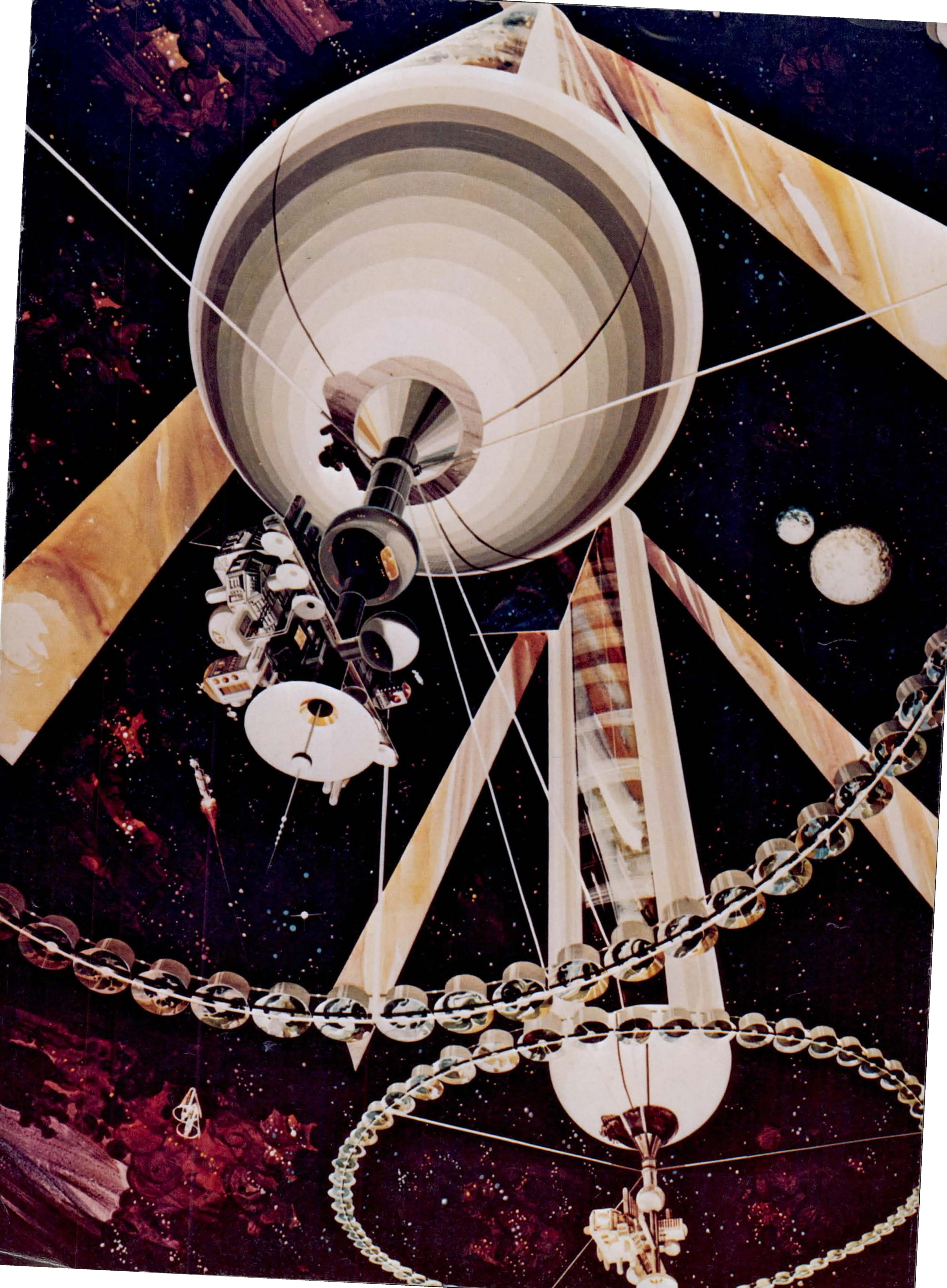
[1] The costs in this article are in terms of 1974 dollars. All costs referenced as coming from it were adjusted to 1975 dollars by taking into account the inflation that occurred in the energy market during 1974. These adjusted prices were obtained from Manne by personal communication on Nov. 17, 1975.



7. View to the Future

In earlier chapters conservative projections are made on the possibilities of space colonization. The view is that the potentialities of the concept are substantial even if no advanced engineering can be employed in its implementation. Abandoning a restriction to near-term technology, this chapter explores long-term development in space, mindful of a comment made many years ago by the writer Arthur C. Clarke. In his view, those people who attempt to look toward the future tend to be too optimistic in the short run, and too pessimistic in the long run. Too optimistic, because they usually underestimate the forces of inertia which act to delay the acceptance of new ideas. Too pessimistic, because development tends to follow an exponential curve, while prediction is commonly based on linear extrapolation.

What might be the higher limits on the speed and the extent of the development in space? First, consider some of the benefits other than energy which may flow from space to the Earth if the road of space colonization is followed. To the extent that these other benefits are recognized as genuine, space colonization may take on added priority, so that its progress will be more rapid.

From the technical viewpoint, two developments seem almost sure to occur: progress in automation, and the reduction to normal engineering practice of materials technology now foreseeable but not yet out of the laboratory. Those general tendencies, in addition to specific inventions not now foreseen, may drive the later stages of space colonization more rapidly and on a larger scale than anticipated in the other chapters of this report.

BENEFITS NOT RELATED TO ENERGY

Space colonization is likely to have a large favorable effect on communication and other Earth-sensing satellites. Already communication satellites play an important role in handling telex, telephone, computer, and TV channels. They provide data-links and track airplanes and ships as well as rebroadcast TV to remote areas. In the future even more of these data-link applications can be expected. Not only will planes and ships be tracked and communicated with by using satellites, but trains, trucks, buses, cars, and even people could be tracked and linked with the rest of the world continuously. Currently, the main obstacle blocking direct broadcasting of radio and TV to Earth from orbit is the lack of low-cost power in space. SSPS's would produce such power. In addition, their platforms could be used to provide stability. Currently, up to 40 percent of the in-orbit mass of communication satellites consists of equipment used to provide power and maintain stability. Finally, colonists could carry out servicing and ultimately build some of the components for such satellites.

Space manufacturing such as growing of large crystals and production of new composite materials can benefit from colonization by use of lunar resources and cheap solar energy to reduce costs. Space manufactured goods also provide return cargo for the rocket traffic which comes to L_5 to deliver new colonists and components for SSPS's.

Within the past half-century many of the rich sources of materials (high-grade metallic ores in particular) on which industry once depended have been depleted. As the size of the world industrial establishment increases, and low-grade ores have to be exploited, the total quantity of material which must be mined increases substantially. It is necessary now to disfigure larger sections of the surface of the Earth in the quest for materials. As both population and material needs increase, the resulting conflicts, already noticeable, will become more severe. After the year 2000 resources from the lunar surface or from deep space may be returned to the Earth. Much of the lunar surface contains significant quantities of titanium, an element much prized for its ability to retain great strength at high temperature, and for its low density. It is used in the airframes of high performance aircraft, and in jet engines. Given the convenience of a zero-gravity industry at L_5, a time may come when it will be advantageous economically to fabricate glider-like lifting bodies in space, of titanium, and then to launch them toward the Earth, for entry into the atmosphere. The transportation of material to the Earth in this form would have minimum environmental impact, because no rocket propellant exhaust would be released into the biosphere in the course of a descent. (Some oxides of nitrogen would be formed as a result of atmospheric heating.) Titanium may be valuable enough in its pure form to justify its temporary fabrication into a lifting-body shape, and its subsequent retrieval in the ocean and towing to port for salvage and use. If such lifting-bodies were large enough, it might be practical to employ them simultaneously as carriers of bulk cargo, for example, ultra-pure silicon crystals zone-refined by melting in the zero-gravity environment of the L_5 industries. It has been suggested that the traditional process of metal casting in the strong gravitational field of the Earth limits the homogeneity of casts because of turbulence due to thermal convection. Quite possibly, in space, casting can be carried out so slowly that the product will be of higher strength and uniformity than could be achieved on Earth. A titanium lifting-body might carry to the Earth a cargo of pure silicon crystals and of finished turbine blades.

RESEARCH IN DEEP SPACE

The foundries of the Earth fabricate heavy machinery in an intense gravitational field simply because there is no other choice. The ideal location for the construction of a very large object is almost certainly a zero-gravity region. The L_5 colonies, furnished with abundant solar power, relatively conveniently located for access to lunar materials, and with zero gravity at their "doorsteps" will very likely become the foundries of space, manufacturing not only satellite power stations but also radio telescope antennas many kilometers in dimension, optical telescopes of very large size, and vessels intended for scientific voyages to points farther out in space. Research probes to the asteroids and to the outer planets could be built, checked out and launched gently from L_5 colonies and with none of the vibration which attends their launch from the surface of the Earth. Once the principles of closed-cycle ecology have been worked out thoroughly, as they almost surely will be during the first few years of colonization, a vessel large enough to carry a "laboratory village" of some hundreds of people could be built at L_5 and sent forth on an exploratory trip of several years. On Earth, villages of smaller size have remained stable and self-maintaining over periods of many generations, so there seems no reason why a trip of a few years in the spirit of one of Darwin's voyages could not be undertaken in deep space.

Lunar resources, when available, will have a profound impact on the cost of travel between low Earth orbit (LEO) and L_5. Indeed, an ordinary chemical rocket, able to reload with liquid oxygen at L_5, and to carry only hydrogen as a propellant component from the Earth, would perform as a LEO-to-L_5 shuttle. For a trip from L_5 out to the asteroids, it may be that eventually each exploratory ship will carry enough propellant for only a one-way trip, relying on the carbonaceous chondritic asteroids as inexhaustible "coaling stations" for hydrogen and oxygen, thereby making longer voyages possible.

ROCKET ENGINES FOR DEEP SPACE

For operations from Earth a rocket engine has to be compact and very strong, capable of withstanding high temperatures and pressures. For voyages between L_5 and the asteroids there is no need for rapid acceleration, and in zero gravity there is no reason why an engine could not be many kilometers in length and quite fragile. One obvious candidate for a deep-space rocket engine is the "mass-driver" which would, presumably, be proven and reliable even before the first space colony is completed. For deep-space use a solar-powered mass-driver could be as much as 50 km in length, made with yard-arms and guy-wires, much like the mast of a racing vessel. Note that on the surface of the Earth, in one gravity, it is possible to build very lightweight structures (television towers) with a height of 500 m. For deep space an acceleration of 10^{-4} g would be sufficient, so it should be possible without excessive structure to build something much longer.

A mass-driver optimized for propulsion rather than for materials transport would have a lower ratio of payload mass to bucket mass than is baselined for the Moon. For a length of 50 km an exhaust velocity of as much as 8 km/s (in rocketry terms, a specific impulse of 800) should be possible without exceeding even the present limits on magnetic fields and the available strengths of materials. A mission to the asteroids, with an exhaust velocity that high, would require an amount of reaction mass only a little more than twice as large as the final total of payload plus engine.

A mass-driver with a length of 50 km could hardly be made in a miniature version; it would probably have a mass of some thousands of tonnes, a thrust of about 10,000 newtons, and would be suitable as the engine for a ship of several tens of thousands of tonnes total mass.

TRANSPORT

In the course of the first decades of colonization it seems likely that solar-cell powerplants for space vehicles will decrease in mass, ultimately becoming very light. It will not be economically reasonable to continue using rocket engines which exhaust hydrogen, scarce as it is on the Moon. The rocket engines of that period will very likely be solar-powered, and must exhaust as reaction mass some material that appears naturally as a waste-product from the processing industries in space; further, that material must not be a pollutant. One good candidate may be oxygen; it constitutes 40 percent by weight of the lunar soils.

At least two types of rocket engines satisfying these conditions seem good possibilities: the mass-driver, used with liquid or solid oxygen payloads for reaction mass, and the colloidal-ion rocket, which would accelerate electrically small micropellets having a ratio of charge to mass which is optimized for a particular mission. The mass-driver, as a rocket engine, only makes sense for large vehicles or loads; its length would be comparable to that of an SSPS, and its thrust would be several thousand newtons. The colloidal-ion rocket would have much lower thrust but could be compact.

When traffic between the Earth and the colonies becomes great enough, the most economical system may consist of a single-stage-to-orbit shuttle between Earth and LEO. Because there would be no need for the transport of large single structures, shuttles of that kind could be sized for optimum efficiency. From LEO to L_5 the transport problem is entirely different, transit times are several days rather than a few hours, and high thrusts are not required. The most economical vehicles for that part of space may be large ships built at the colonies. These ships, mass-driver powered through solar energy, could carry a round-trip load of oxygen as reaction mass when they leave the colonies, and could then rendezvous with shuttles in low orbit. The outbound trip would be faster than the inbound.

THE ASTEROIDAL RESOURCES

The evidence is mounting that a substantial fraction, if not actually a majority, of the asteroids are made up of carbonaceous chondritic material. If so, the asteroids contain an almost inexhaustible supply of hydrogen, nitrogen and carbon. In energy (namely: in velocity interval squared) the asteroids are about as distant from L_5 as is the surface of the Earth: the velocity change to either destination, from L_5, is 10 to 11 km/s. This is about four times that between L_5 and the Moon. For some time, then, it seems likely that the asteroidal mines will be exploited mainly for the "rare" elements rather than for those which can be obtained from the Moon. Ultimately, as industry shifts from L_5 out toward the asteroids, lunar resources may be used less as materials are mined and used directly, without the necessity of prior shipping.

NEW METHODS OF CONSTRUCTION

Construction methods which are now only at the stage of laboratory test may be practiced only in the space environment. In zero gravity and with a good vacuum, it may be practical to form a shell by using concentrated solar heat to melt aluminum or another metal at the center of a thin form. Evaporation over a period of months or years would build up on the form a metal shell, for which the thickness at each point would be controlled by masking during the evaporation. This process would lend itself well to automation.

Alternatively, or in addition, habitat sections could be constructed of fiber-composites. On Earth, the most familiar example of such a material is fiberglass, a mixture of glass threads in an organic matrix. Boron filaments are used in place of glass for high strength in aerospace applications. Glass fiber could easily be made from lunar materials. As a matrix, a silicon compound might be used in the space environment similar to a corresponding carbon-based organic. Such a compound might be attacked by the atmosphere if it were used on Earth, but could be quite stable in vacuum.

HABITAT DESIGN

In the long run, as colony size approaches diameters of several kilometers and individual land areas of more than 100 km^2, the cosmic-ray shielding provided by the colony land area, structure, and atmosphere becomes great enough so that no additional shielding need be added, allowing the development of large-size colonies earlier than can otherwise be justified on economic grounds. Mankind's descendents who may live in space during the next century will probably be far more adventurous in their choice of styles of habitation than can now be projected, and in the spirit of this section, a relaxation of strict choices of physiological parameters seems permissible.

The assumption that the retention of artificial gravity in the living habitat continues to be necessary may be rather conservative. This assumption is based on human nature. Most people do not keep in good physical condition by self-imposed exercise. Return to Earth, whether or not occurring, must remain an option with strong psychological overtones. To rule it out, as might be the case if bones and muscles were allowed to deteriorate too far by long habitation in zero gravity, would be to make of the colonists a race apart, alien to and therefore quite possibly hostile to those who remain on Earth.

Habitation anywhere within a range of 0.7 to 1.0 g is assumed to be acceptable, and in the course of a normal day a colonist may go freely between home and zero-gravity work or recreation areas.

As colony size increases, the rotation-rate criterion ceases to be a design limit. Atmospheric pressure is important to large colonies. With increasing experience in an environment of very large volume, with an abundant source of water, and with artifacts made for the most part of minerals rather than organics, fire protection is expected to be practical in an atmosphere having a total pressure of 36 kPa, of which half is oxygen. The oxygen at Denver, Colorado (which is 18 kPa), is normal for millions of human beings in that area. It is no great leap to assume an atmospheric mix of 50 percent oxygen, 50 percent nitrogen with appropriate amounts of water vapor.

From the esthetic viewpoint, people might prefer an "open" nonroofed design habitat (sphere or cylinder) when it is available to one of the more mass-efficient roofed designs. It may be possible to get some better information about public preference after further exposure of the ideas to the public. Architectural design competitions could be a means to yield valuable new ideas. It seems certain that over a time-span of several decades new designs will evolve. Some may combine mass-efficiency, achieved by optimizing the shape of the pressure shell and the cosmic-ray shield, with visual effects which are tailored to meet the psychological needs of the colony's people. The ways in which sunlight is brought into a habitat may be adjusted to suit psychological needs which we on Earth do not yet appreciate. Similarly, the degree of visual openness of a habitat may be separated from the structure itself; it is possible to divide an open geometry into visual subsections, and to provide visual horizons in a variety of ways, though a closed geometry cannot easily be opened.

To estimate the total resources of land area which could ultimately be opened by space colonization requires a model. An example from what might be a class of geometries is the "Bernal sphere" discussed in chapter 4, which seems representative of possible designs of interest. As far as now known the Bernal sphere is more suitable than other geometries for the addition of passive cosmic-ray shielding, and for a given diameter it is far more efficient in mass than the cylinder geometries. Quite possibly, of course, other designs not yet thought of may be found more desirable in the long run. A spherical habitat of 900 m radius, rotating at 1 rpm, and containing an atmosphere with a total pressure of 36 kPa, with Earth-normal gravity at its "equator," has a structural mass of 5×10^6 t if made of aluminum. Its habitable area is 6.5 km^2, in the form of a single connected region 1400 m wide and 5.6 km in circumference. It has agricultural areas of comparable size, and low-gravity regions for heavy assembly, and for recreation. Its stationary or slowly counter-rotating cosmic-ray shield has a mass of 6×10^7 t, about 5.5 times larger than that of the torus design. Assuming a population density equal to that of the baseline design, such a sphere can support a population of about 140,000 people. However, it is probable that habitats of such a size would be settled with much lower population densities, so as to permit additional "wild" areas and parkland.

AUTOMATION AND PRODUCTIVITY

As the space community produces increased revenue, the standard of affluence is expected to increase. Increased use of automation and adjustment of levels of employment may permit the construction of habitats with a greater amount of area per person. Also, esthetic considerations will have greater impact on habitat design and architecture as habitat construction continues and per-capita wealth increases.

If automation permits a moderate increase of productivity to a value of 100 t/person-year, which is twice the value now appropriate for processing and heavy industries on Earth, the large Bernal sphere could be built for an investment of 50,000 man-years of labor. That is equivalent to the statement that 12 percent of the maximum population of one such sphere, working for 3 yr could duplicate the habitat. Automation is much better suited to the large scale, repetitious production operations needed for the habitat shell than to the details of interior architecture and landscape design. It seems quite likely, therefore, that the construction of new habitats will become an activity for specialists who supply closed shells, ready for interior finishing, to groups of prospective colonists.

LIMITS TO GROWTH

From the viewpoint of economics, the logical site for colony construction is the asteroid belt itself. The construction equipment for colony-building is much smaller in mass than the raw materials it processes. Logically the optimum method is to construct a new habitat near an asteroid, bring in its population, and let them use the colony during the period of about 30 yr it takes to move it by a colloidal-ion rocket to an orbit near L_5. They may, however, prefer to go the other way, to strike out on their own for some distant part of the solar system.

At all distances out to the orbit of Pluto and beyond, it is possible to obtain Earth-normal solar intensity with a concentrating mirror whose mass is small compared to that of the habitat.

If the asteroids are ultimately used as the material resource for the building of new colonies, and if by constructing new colonies near asteroids relatively little reaction mass is wasted in transportation, the area of land that is made available on the space frontier can be estimated. Assuming 13 km of total area per person, it appears that space habitats might be constructed that would provide new lands with a total area some 3,000 times that of the Earth. For a very long time at least mankind can look toward resources so nearly inexhaustible that the current frustration of limits to growth can be replaced by a sense of openness and the absence of barriers to further human development.

Size of an Individual Habitat

The structural shell which contains the forces of atmospheric pressure and of rotation need not, in principle, itself be rotated. In the very long term, it may be possible to develop bearings (possibly magnetic) with so little drag that a structural shell could be left stationary while a relatively thin vessel containing an atmosphere rotates inside it. Such a bearing cannot be built now, but does not seem to violate any presently known laws of physics. An invention of that kind would permit the construction of habitats of truly enormous size, with usable areas of several thousand km^2.

Even in the absence of a "frictionless" bearing, the size possibilities for an individual habitat are enormous. As an example, a large titanium sphere seems technically feasible of a diameter of 20 km. It would contain an atmosphere at about 18 kPa pressure of oxygen and be rotated to provide Earth normal gravity at its equator. The usable land area is several hundred km^2, comparable to the size of a Swiss canton or to one of the English shires.

The Speed of Growth

It may be that the residents of space, enjoying a rather high standard of living, will limit their population growth voluntarily, to zero or a low value. Similar populations, on Earth, underwent a transition of that kind in passing from an agrarian to an affluent industrial society. Economic incentives for having a substantial workforce in space may, however, drive the rapid construction of new industries and new habitations there. An upper limit to the speed of growth of space colonization is estimated by assuming 3 yr for the duplication of a habitat by a workforce equivalent to 12 percent of a habitat's population. Only 56 yr are required at this rate for the construction of communities in space adequate to house a population equal to that of the Earth today.

The Decrease of Population Density With Time

Here on Earth it seems impossible for the population to increase without a corresponding increase in crowding because economics force concentrations into cities. It is expected that with the passage of time the population density must almost certainly decrease, irrespective of the total number of colonists. It is fundamental to the colonization idea that productivity can continue to grow in the colonies. As a consequence there is a continued growth of energy usage per person. As an example, suppose that there is a real (noninflationary) productivity growth rate of 2.5 percent per year and a 1:1 relationship between this productivity growth rate and the increase in energy usage. That implies a growth of a factor of 24 in total energy usage over a 128-yr period (1976 to 2104).

SOME ECONOMIC CONSIDERATIONS

Space colonization appears to offer the promise of near-limitless opportunities for human expansion, yielding new resources and enhancing human wealth. The opening of new frontiers, as it was done in the past, brings a rise in optimism to society. It has been argued that it may also enhance the prospects of peace and human well-being. Just as it has been said that affluence brings a reduction in the struggle for survival, many have contended that expansion into space will bring to human life a new spirit of drive and enthusiasm.

Space community economies will probably be extensions of those of Earth for some time to come. There is, however, room to speculate as to how locational differences may enhance organizational differences. There is, for example, some evidence that the societies in the lands settled in recent periods have tended to display differences from those settled further in the past; for example, one can compare the U.S. society and economy to that of the British, or the economy and society of California with that of Massachusetts.

It may be that the shared circumstances of risk associated with early colonization will bring the earlier settlers into a close relationship. This, and the problems of access to Earth-produced products, may foster a sense of sharing and of cooperation, more characteristic of a frontier than of a mature Western society. With the increase of colony population, the impersonality characteristic of modern terrestrial societies would be expected to emerge.

Ownership and proprietary rights may be somewhat different from those found on Earth in part because the environment within space habitats will be largely man-made. The balance of privately-controlled vs. publicly-controlled space may be significantly influenced by these closely similar environmental experiences. On the other hand, the cultural inheritance of social forms from the Earth will serve to inhibit utopian impulses toward leaving the ills of human life behind. For example, it is unlikely that any serious development toward egalitarianism in the personal distribution of income will be found to arise in the colonies of the future.

That boundless energy may lead to boundless wealth is a belief which will doubtless be tested in such future developments. Successful exploitation of the extraterrestrial environment is expected to enhance the standard of living not only of the population in space but the population remaining on Earth as well.

With the advent of the era of extraterrestrial communities, mankind has reached the stage of civilization where it must think in terms of hitherto unknown cultural options. In the extraterrestrial communities, many of the constraints which restrict the life on the Earth are removed. Temperature, humidity, seasons, length of day, weather, artificial gravity and atmospheric pressure can be set at will, and new types of cultures, social organization and social philosophies become possible. The thinking required is far more than technological and economic. More basically it is cultural and philosophical.

This new vista, suddenly open, changes the entire outlook on the future, not only for those who eventually want to live in extraterrestrial communities but also for those who want to remain on the Earth. In the future, the Earth might be looked upon as an uncomfortable and inconvenient place to live as compared to the extraterrestrial communities. Since a considerable portion of humanity – even most of it – with ecologically needed animals and plants may be living outside the Earth, the meaning, the purpose, and the patterns of life on Earth will also be considerably altered. The Earth might be regarded as a historical museum, a biological preserve, a place which contains harsh climate and uncontrolled weather for those who love physical adventure, or a primitive and primeval place for tourism. This cultural transition may be comparable to the transitions in the biological evolution when the aquatic ancestors of mammals moved onto land or when Man's quadrupedal ancestors became bipedal and bimanual. The opportunity for human expansion into space is offered; it needs only to be grasped.

8. Recommendations and Conclusions

In the course of the 10-week study, it became apparent that there are many aspects of the design of a space colonization project for which the necessary data are not available. Many are critical to the design so that, in the absence of firm data, conservative assumptions had to be made. This forced the overall design in a conservative direction with considerable weight, size and cost penalties compared with what might be an optimum design.

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT IN CRITICAL SUBSYSTEMS

Before a detailed practical design of a space colony can be undertaken, the following subjects must be researched to fill in the gaps in current design-related data.

1. *Acceptable Radiation Dose.* The 0.5 rem per yr radiation dose is achieved in this design study by accepting a considerable penalty in weight and system complexity. This dosage rate is the upper limit allowed for the general population in the United States and is chosen arbitrarily as a conservative measure. Extensive biological testing should be undertaken to establish a realistic dose limit taking into consideration the colony's population distribution and the scenarios for habitation of the colony. The effect of radiation on agricultural specimens also needs study to assure stable food supplies.

2. *Acceptable g Levels.* The physiological effects of zero-g are serious for long-duration exposure in space. For this reason and since little is known about exposure at intermediate g levels, 1 g was chosen as the design standard. The 1-g choice has significant influence on the design and may be unnecessarily high. An examination of physiology under partial g is required in the Spacelab and subsequent space station missions to determine the minimum g value for which there are no serious long-term physiological effects upon humans.

3. *Maximum Acceptable Rate of Habitat Rotation.* The rate of rotation required to achieve the desired pseudogravity has substantial impact on the design. Since the g-level and rate of rotation determine colony dimensions to a large extent (and thus the weight) determination of an acceptable rate of rotation is important. While it is difficult to test human vestibular functions in a realistic way on Earth, it is critical that a better understanding of the subject be obtained by studies both on Earth and in space.

4. *Closure of the Life Support System.* The critical role of agriculture in providing food and regenerating the atmosphere in the colony requires that it be undertaken with utmost confidence and understanding. The components of the agricultural system require study to determine their detailed characteristics and their suitability. While possible in theory, large living systems have never been operated in a closed loop. First on a small scale, and finally on a large scale, complete closure of a demonstration life support system should be accomplished before colonization begins. The requirements for microbial ecology need to be studied.

5. *Intensive Agriculture.* The support of the colony's inhabitants on the agricultural output from 150 acres is based on highly intensive photosynthetic production, beyond that realized to date. The exact enhancement of yields from lighting, increased carbon dioxide, and regular irrigation needs to be determined, and actual prototype farming needs to be conducted prior to closed life support system tests.

6. *Methods of Radiation Shielding.* The requirement for 10 million tonnes of passive shielding resulted from uncertainty in the effectiveness and the complications of active shielding techniques. In particular, it is recommended that studies be undertaken with the plasma shield to achieve the acceptable dose with a workable system.

7. *Productivity in Space.* The size, cost, and schedule for colony (and SSPS) construction are critically dependent upon the number of workers and their productivity. Terrestrial examples of worker productivity may be unrealistic for colony construction. Significantly greater definition of worker productivity is required for the colony design and should be accompanied by actual experimentation in space to derive realistic quantitative data.

8. *Processing of Lunar Surface Material.* The aluminum and titanium extraction and refining processes suggested by this study are novel and largely unstudied because of the unusual nature of the lunar ores compared to terrestrial ores. The need to develop these processes in the laboratory, the terrestrial pilot plant,

and eventually the space pilot plant is critical to the success of the program. Efficient production of glass from lunar rock is also required under the limitation of minimal additives. Physical and optical properties of the resulting glass also need to be determined.

9. *Lunar Mass Launcher.* The efficient transfer of lunar ore to a space processing facility is essential to the success of the space colonization concept. Alternative methods (such as the gas gun) need further study so that a careful design analysis can be made of the entire subsystem. A scaled prototype should be tested. More detailed engineering analysis of the baseline system is required.

10. *Mass Catcher.* The location and operational principle of the mass catcher are critical to space colonization and weakly substantiated in this study. The entire subsystem needs much greater study and eventually testing in space.

11. *Minimum Acceptable Partial Pressure of Nitrogen and Oxygen in the Space Colony Atmosphere.* To minimize the quantity of nitrogen brought from Earth, the problems resulting from oxygen-rich atmospheres need detailed study to determine the minimum amount of nitrogen required in the atmosphere.

12. *Satellite Solar Power Station Design.* This study did not focus on the details of the SSPS design. The method of energy conversion (photoelectric vs. thermal-mechanical) needs to be selected on the basis of detailed comparative study and perhaps on the basis of fly-off testing on small-scale prototypes. The methods of construction need careful examination from the viewpoint of efficient material and manpower utilization.

13. *Transportation System.* In addition to the main transportation elements (the HLLV, the mass launcher, and mass catcher), the rotary pellet launcher and the ferrying ion engines require research and development. While the HLLV is proposed within the current baseline, even more advanced vehicles with larger payloads and lower launch costs would be of enormous benefit to the space colonization program at any time in the program.

14. *Environmental Impacts.* The frequency of launches needed and the products from rocket combustion need to be studied to determine the impact upon the Earth. The high power microwave beam from the SSPS may have effects on certain biota in or near the beam, and rf interference with communications, terrestrial navigation and guidance systems, and radio astronomy should be examined.

15. *Human Physical, Psychological, Social, and Cultural Requirements for Space Community Design.* The diversity of options and the uncertainty of absolute requirements for various human factors require considerable study, elaboration, and agreement. Factors governing design include habitat configuration, efficient utilization of area, methods and diversity of construction, visual sensations, and colonist activities. All need to be thoroughly evaluated.

16. *Political, Institutional, Legal, and Financial Aspects of Space Colonization.* The space colonization effort is of such magnitude that it requires careful analysis with respect to organization and financing. For this analysis competent, realistic, and thorough study is needed. National versus international, and governmental versus private or quasi-governmental organization, requires study and evaluation. The operational organization for space colony implementation is of sufficient magnitude to merit this study being made very early in consideration of a program to establish human habitats in space.

17. *Economic Analysis of Space Colonization Benefits.* A more sophisticated analysis is needed to determine whether the benefits of space colonization do or even should justify the costs. In particular, studies are needed which compare space colonization and SSPS production with alternative methods of producing electricity.

18. *Additional Topics for Later Study.* Space colonization in general covers such a wide spectrum of diverse topics as to allow many fruitful studies with varying depths of analysis. Examples of subjects that need to be investigated are:

a. Method of immigrant selection.

b. Effect of "deterrestrialization" of colonists.

c. Effects of large-scale operations on the lunar, cislunar, and terrestrial environment, and effects on the solar wind.

d. Disposal of nuclear waste on the lunar surface.

e. Alternate colony locations (such as lunar orbit, L_2, LEO inside Van Allen belt, free orbit, near asteroids, Jupiter orbit).

f. Detailed metabolic requirements (input and output data) for plants and animals.

g. Suitability of condensed humidity for human consumption, for fish, and for crop irrigation.

h. Recycling of minerals from waste processing.

i. Production of useful products from plant and animal processing byproducts.

j. Characterization of trajectories from lunar surface to the various loci of potential activity.

k. Analysis of the potential foreign market for electric power.

l. Quantitative analysis of nonelectrical space benefits, for example, benefits from production of communication satellites in space.

m. Development of alternative mission profiles which increase emphasis on SSPS production or on colony production.

n. Effect of an established space colony on future space missions, their feasibility and cost.

o. Application of learning curves to space colonization.

p. Ecological balance within the colony, microbial and insect ecologies (including role of nitrogen fixation).

q. Chemical processing with nonaqueous or even gaseous techniques.

r. Determination of the proper safety margins for various systems.

s. Detailed design of windows and their optical properties.

t. Dynamics of atmospheres in rotating structures.

u. Tools and techniques for working in zero g.

v. Rendezvous with asteroids.

w. Remote assembly of large structures.

x. Halo orbits.

y. Description of everyday phenomena in a rotating environment.

z. Fire protection.

aa. Synthetic soils.

bb. Space manufacturing.

cc. Extension of economic geography to space.

dd. Adaptable and evolutionary aspects of habitat design.

ee. Atmospheric leakage rates and gaskets.

ff. A zero-g colony.

gg. Studies of work organization in remote locations.

hh. Studies of social and economic interdependence among communities in remote locations with respect to transportation.

ii. Studies of functional division of labor within human communities.

jj. Study of methods for transporting and storing gaseous materials such as hydrogen and nitrogen in various chemical forms such as ammonia, ammonium salts, or other compounds.

kk. Space viticulture and enological techniques.

ll. Heterogeneity as a desired or required characteristic.

mm. Rotation of habitat within the shield.

nn. Colony governance.

oo. Requirements for interior illumination. Is sunlight really needed in living and even agricultural areas?

pp. A detailed list of colonist activities and the land area usage dictated by analysis of interior illumination needs.

qq. Composite material fabrication techniques in space.

rr. Construction of lunar mass launcher from lunar materials using bootstrapped pilot plants.

ss. Detailed study and list of materials to be imported from Earth to support the everyday needs of the colony.

tt. Extrusion techniques for space.

uu. Alternative diet components.

vv. An acceptable name for the first colony.

RECOMMENDATIONS FOR SPACE VENTURES

A principal recommendation of this summer study is that a major systems study be made of space industrialization and space colonization. In addition, it is recommended that the following space ventures be undertaken as necessary preludes to space colonies.

1. Continue development of the space transportation system (shuttle) and of Spacelab.
2. Start development of the shuttle-derived Heavy-Lift Launch Vehicle.
3. Construct a large space laboratory for placement in low-Earth orbit in which experiments necessary to space colonization can be carried out.
4. Establish a lunar base to explore and to test for the availability of lunar resources.
5. Send an unmanned probe to the asteroids to determine their chemical composition.

CONCLUSIONS

Space colonization is desirable because of the hope it offers humanity. A sense of the limits of Earth has been heightened in recent years by growing awareness of the delicate ecological balance of the planet, its finite resources and its burgeoning human population. The sense of closure, of limits, is oppressive to many people. In America, growth has been the vehicle of rapid and often progressive change; it has been the source of opportunity for millions of people and has played an important role in fostering American democracy and political freedoms. To have opportunities restricted and to be forced to devise political institutions to allocate equitably, resources insufficient to meet demand, are unpleasant prospects. Space offers a way out, with new possibilities of growth and new resources. Space offers a new frontier, a new challenge, and a hope to humanity, much as the New World offered a frontier, a challenge, and a hope to Europe for more than 4 centuries.

Space also offers riches: great resources of matter and energy. Their full extent and how they might be used are not altogether clear today. It is likely that solar energy collected in space, converted to electricity, and beamed to Earth would be of great value. The manufacture of the satellite power stations to bring this energy to Earth and of other commercial activities that use the abundant solar energy, the high vacuum, and the weightlessness available in space, might bring substantial returns to investors. It seems possible that the historic industrialization of Earth might expand and go forward in space without the unpleasant impacts on the Earth's environment that increasingly trouble mankind. On the other hand, the potential of space must not detract from efforts to conserve terrestrial resources and improve the quality of life on Earth.

On the basis of this 10-week study of the colonization of space there seems to be no insurmountable problems to prevent humans from living in space. However, there are problems, both many and large, but they can be solved with technology available now or through future technical advances. The people of Earth have both the knowledge and resources to colonize space.

It is the principal conclusion of the study group that the United States, possibly in cooperation with other nations, should take specific steps toward that goal of space colonization.

UNITS AND CONVERSION FACTORS

A	angstrom	a unit of length most often used in reference to the wavelength of light $= 10^{-10}$ m
atm	standard atmosphere	a unit of pressure based on a standardized sea level terrestrial atmospheric pressure = 14.7 psi = 760 mm Hg = 1.0132 bars = 101.325 kPa
AU	astronomical unit	a unit of length used in astronomy and astronautics, referenced to the mean distance between Earth and Sun = 149,600,000 km = 92,961,000 mi
C	coulomb	a unit of electrical charge equal to the amount of electricity transferred by a current of 1 ampere for 1 second
cal	calorie	a unit of energy equal to the amount necessary to raise 1 g of water 1° C = 4.1868 J
Cal	large calorie	a unit of energy used in reference to the energy content of food = 1000 cal
eV	electron volt	a unit of energy used in particle physics, the amount of energy acquired by an electron in being accelerated through a potential difference of 1 volt $= 1.60219 \times 10^{-19}$ J
g	"gee"	the acceleration of gravity at the mean surface of the Earth $= 980.665$ cm/s^2 $= 32.174$ ft/s^2
g	gram	a unit of weight in the metric system = 0.03527 oz (avoirdupois)
ha	hectare	a metric unit of area used in field measurements $= 100$ m $\times$ 100 m, i.e., 10^4 m^2 = 2.471 acres

Hz	hertz	a unit of frequency = cycle/s
J	joule	unit of energy or work; the work done when the point of application of 1 newton moves a distance of 1 meter in the direction of the force = 10^7 ergs = 23.02 ft poundals
m	meter	metric unit of length = 3.2808 ft
mil	mil	a unit of cost = $0.001
N	newton	unit of force in the meter-kilogram-second system; that force which gives to a mass of 1 kilogram an acceleration of 1 m/s^2 = 10^5 dynes = 7.015 poundals
Pa	pascal	a unit of pressure = 1 N/m^2 = 10^{-5} bar = 0.0000098 atm = 0.0001372 psi
rad	rad	a unit of absorbed radiation dosage = 10^{-2} J/kg = 100 ergs/g
R	roentgen	a unit of absorbed radiation based on the amount of ionization produced in tissue = 2.58×10^{-4} coulombs/kg (defined strictly as the amount of gamma radiation sufficient to produce ions carrying one electrostatic unit of charge in one cubic centimeter of air; but loosely used to apply to any ionizing radiation producing the same effect)
rem	rem	the roentgen equivalent, man; expresses the relative biological effect of different types of radiation For X-rays, 1 rem results from the exposure of 1 roentgen.

t	tonne	used as a metric unit of mass for large masses = 1000 kg = 0.98 tons (long) = 1.10 tons (short)
T	tesla	a unit of magnetic flux density = 1 Wb/m^2
W	watt	unit of power = 1 J/s = 10^7 ergs/s = 23.02 ft poundals/s = 1.301×10^{-3} horse power
Wb	weber	unit of magnetic flux; the flux which produces an electromotive force of one volt in a circuit of one turn when this flux is reduced to zero at a uniform rate in one second

Metric Prefixes Used

Prefix	Name	Multiplication factor	Example	
G	giga	billion (10^9)	GW	= gigawatt = 1 billion watts
M	mega	million (10^6)	MeV	= million electron volts
k	kilo	thousand (10^3)	km	= kilometer (0.6214 miles) = 1000 meters
c	centi	hundredth (10^{-2})	cm	= centimeter (2.54 inches)
m	milli	thousandth (10^{-3})	mm	= millimeter
μ	micro	millionth (10^{-6})	μm	= micrometer = one millionth of a meter

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